



Environmental Technology Verification Report

Environmental Decision Support Software

C Tech Development Corporation

Environmental Visualization System Pro (EVS-PRO)

ETV ✓ ETV ✓ ETV ✓

**THE ENVIRONMENTAL TECHNOLOGY VERIFICATION
PROGRAM**



ETV Joint Verification Statement

TECHNOLOGY TYPE:	ENVIRONMENTAL DECISION SUPPORT SOFTWARE	
APPLICATION:	VISUALIZATION, SAMPLE OPTIMIZATION, AND COST-BENEFIT ANALYSIS OF ENVIRONMENTAL DATA SETS	
TECHNOLOGY NAME:	Environmental Visualization System Pro (EVS-PRO)	
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification Program (ETV) to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations and stakeholder groups consisting of regulators, buyers, and vendor organizations, with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Site Characterization and Monitoring Technologies Pilot (SCMT), one of 12 technology areas under ETV, is administered by EPA's National Exposure Research Laboratory (NERL). With the support of the U.S. Department of Energy's (DOE's) Environmental Management program, NERL selected a team from Brookhaven National Laboratory (BNL) and Oak Ridge National Laboratory (ORNL) to perform the verification of environmental decision support software. This verification statement provides a summary of the test results of a demonstration of C Tech Development Corporation's Environmental Visualization System Pro (EVS-PRO) decision support software (DSS) product.

DEMONSTRATION DESCRIPTION

In September 1998, the performance of five DSS products were evaluated at the New Mexico Engineering Research Institute, located in Albuquerque, New Mexico. In October 1998, a sixth DSS product was tested at

BNL in Upton, New York. Each technology was independently evaluated by comparing its analysis results with measured field data and, in some cases, known analytical solutions to the problem.

Depending on the software, each was assessed for its ability to evaluate one or more of the following endpoints of environmental contamination problems: visualization, sample optimization, and cost-benefit analysis. The capabilities of the DSS were evaluated in the following areas: (1) the effectiveness of integrating data and models to produce information that supports the decision, and (2) the information and approach used to support the analysis. Secondary evaluation objectives were to examine DSS for its reliability, resource requirements, range of applicability, and ease of operation. The verification study focused on the developers' analysis of multiple test problems with different levels of complexity. Each developer analyzed a minimum of three test problems. These test problems, generated mostly from actual environmental data from six real remediation sites, were identified as Sites A, B, D, N, S, and T. The use of real data challenged the software systems because of the variability in natural systems. The technical evaluation team performed a complete baseline analysis for each problem. These results, along with the data were used as a baseline for comparison with the DSS results.

C Tech Development Corporation staff chose to use EVS-PRO to perform the visualization endpoint on selected data from each of the six sites. In addition, sample optimization was performed for the Site B, N, and S problems, making use of the geostatistical algorithms in EVS-PRO. Cost-benefit analysis (estimates of contaminated volume as a function of cleanup level) was also performed on these three problems and for the Site A cost-benefit problem and the Site D sample optimization problem.

EVS-PRO was used to generate several different types of output as appropriate to the problem under study. Output included three-dimensional (3-D) maps of the regions of contamination above specified threshold concentrations as a function of the probability of exceeding the threshold value. A scale of coordinates and surface features were included on the maps to provide a frame of reference. Where aerial photographs were provided, EVS-PRO superimposed the site maps over the photograph to improve visual understanding of the extent of the problem. For the Site A cost-benefit problem, EVS-PRO also generated an animation that provided a 3-D depiction of the extent of contamination. For the Site T groundwater contamination problem, EVS-PRO generated an animation depicting subsurface soil stratigraphy. These animations rotated the view through 360° to provide the analyst with a more complete view of the data. For Sites B and S, C Tech also provided files generated by EVS-PRO using virtual reality modeling language (VRML) that could be viewed and navigated. Navigation permits the viewer to rotate the image to any angle to gain a better understanding of the extent of contamination. The data from Sites A, B, D, and S were used to generate a cost-benefit analysis of the volume contaminated above the specified contaminant-specific cleanup threshold as a function of probability. For the Site N sample optimization problem, EVS-PRO produced maps of uncertainty as a function of the number of samples collected. This information was used to illustrate the reduction in uncertainty obtained with increased sampling and to highlight regions of high uncertainty that may require further sampling. Several hundred visualizations were produced as part of the demonstration.

Details of the demonstration, including an evaluation of the software's performance, may be found in the report entitled *Environmental Technology Verification Report: Environmental Decision Support Software—C Tech Development Corporation, Environmental Visualization System Pro (EVS-PRO)*, EPA/600/R-00/047.

TECHNOLOGY DESCRIPTION

C Tech's EVS-PRO unites interpolation, geostatistical analysis, and fully 3-D visualization tools into a software system developed to address, among other things, sample optimization and cost-benefit analysis. EVS-PRO's capabilities can be used to provide 3-D maps of geologic structure, subsurface contamination, and regions containing contamination above specified threshold concentrations at a fixed probability level. EVS-PRO can also perform geostatistical analyses that optimize sample locations for site characterization and can estimate volumes and mass of contaminated media for use in cost-benefit analysis. EVS-PRO can quantify the statistical variation in the contaminant volume and mass estimates resulting from the current level of characterization

VERIFICATION OF PERFORMANCE

The following performance characteristics of EVS-PRO were observed:

Decision Support: EVS-PRO provides decision support through 3-D visualization of environmental data such as contaminant concentration contours, quantification of uncertainties in interpolation predictions, recommendation of additional sample location to reduce uncertainties, and providing statistical information about the extent of contamination (e.g., volume contaminated as a function of probability).

Documentation of the EVS-PRO Analysis: For each problem, C Tech provided a detailed description of the steps necessary to import the data into EVS-PRO and perform the desired analysis. The steps proceeded logically, and manipulations to format the data into the EVS format were relatively simple. Numerous files—including visualizations, input files, and output files—were provided for review.

Comparison with Baseline Analysis and Data: EVS-PRO produced visualizations from six different sites. All visualizations produced by EVS-PRO were consistent with the baseline data. Visualizations included 3-D representations of geologic structure, hydraulic head, concentration contours above threshold values, and uncertainty maps. The visualizations accurately incorporated surface features (maps of roads, buildings, water bodies) and aerial photographs when available. Visualizations often provided well and sample locations as a function of elevation. Sample locations were accurately color-coded to match the measured data.

Sample optimization was performed for Sites B, N, and S. The analyses for Site B and S adequately characterized the plume with an acceptable number of additional samples. For the Site N problem, in which the number of samples was limited, the software inadequately characterized the extent of contamination. EVS-PRO was used to provide cost-benefit analysis of the volume of contamination as a function of threshold concentration and probability level for Sites A, B, N, and S. Its volume estimates were often a poor match to the baseline analysis.

EVS-PRO can perform sample optimization analysis to recommend sampling locations and cost-benefit analysis of the volume of contaminated media as a function of probability. To assist the analyst, the software calculates values for the essential parameters used in these analyses based on the data. While the use of these calculated default values makes it easier for the analyst, the values were not always optimal for the sample optimization or cost-benefit analysis. For the Site N sample optimization problem, in particular, approximately a third of the site remained unsampled due to the approach used in EVS-PRO and the limit on the number of samples. For the cost-benefit problems, the estimates of contaminated volumes were often a poor match to the baseline analysis. This was especially true in estimates of volume above the threshold concentration with a low probability of exceeding the threshold. In these situations, the default parameters selected by EVS-PRO often caused predictions of contamination in regions upgradient from the main plume that did not contain data. Operator intervention to optimize model parameters would have led to better, more accurate analyses. The problems identified are a function of the operator and not the software and emphasize the need to have qualified analysts operate the software and for the analyst to examine the model outputs for consistency with the data.

Multiple Lines of Reasoning: EVS-PRO provides a number of different approaches to analyzing and visualizing the data, including control over essential modeling parameters. This permits multiple analyses of the data. The software generates statistical and geostatistical information about the extent of contamination, thus providing multiple evaluations to assist in data interpretation. The use of EVS-PRO to generate multiple lines of reasoning assists the analyst in conducting a thorough evaluation of the data.

In addition to performance criteria, the following secondary criteria were evaluated:

Ease of Use: EVS-PRO is a sophisticated software product with over 150 computational or visualization modules. The use of visual programming to link the modules makes EVS-PRO fairly easy to use. Most environmental analysts would be able to use the major features of EVS-PRO after two days of training. Advanced features such as use of the scripting language would require more training. An inconvenience of EVS-PRO is its requirement of a fixed-format data field for input files. However, this limitation has been removed in the most recent version of EVS-PRO.

Efficiency and Range of Applicability: EVS-PRO efficiently imported, analyzed, and visualized environmental data sets. In the demonstration, the software analyzed four complete problems (three sample optimization/cost-benefit problems and one cost-benefit problem) and two partial problems (perform visualization) with eight person-days of effort. Of these, approximately four days were spent analyzing the data and four days were spent preparing the report.

Operator Skill Base: For efficient use of the basic features in EVS-PRO, the operator must have knowledge about contouring environmental data sets and managing database files. To use the advanced geostatistical and statistical features, the operator should be knowledgeable in these areas.

Platform: During the demonstration, EVS-PRO was run on a Windows 95 operating system. The computer used for the demonstration was a Pentium II 400 with a Titan II graphics card, 128 MB of RAM, a 4 GB-hard drive, and a 20X CD-ROM.

Training and Technical Support: C Tech provides an extensive users' manual documenting code operation and use. Self-paced training modules are available as part of the software package. Technical support is supplied over the Internet and through e-mail. Training courses are available throughout the year.

Cost: For a single user EVS-PRO sells for \$9995. The EVS pricing structure depends on the product and number of licenses sold to the customer. Discounts are available to educational institutions.

Overall Evaluation: The main strengths of EVS-PRO are its outstanding 3-D visualization capabilities and its capability to rapidly process, analyze, and visualize data. The range of visualization output formats and their quality define EVS-PRO as a premier, state-of-the-art visualization system. Its ability to sort and query the data and write scripts to automate repetitive tasks permits EVS-PRO to examine large amounts of data and quickly generate visualizations of the data in many depiction and animation formats. EVS-PRO's object-oriented programming structure allows the many modules to be easily linked together to perform a complex analysis. EVS-PRO is a mature software program that does not have any major limitations.

A credible computer analysis of environmental problems requires good data, reliable and appropriate software, adequate conceptualization of the site, and a technically defensible problem analysis. The results of the demonstration showed that the EVS-PRO software can be used to generate reliable and useful analyses for evaluating environmental contamination problems. This is the component of a credible analysis that can be addressed by the software; other components, such as proper conceptualization and use of the code, depend on the analyst's skills. The results of an EVS-PRO analysis can support decision-making. EVS-PRO has been employed in a variety of environmental applications. Although the EVS-PRO software has been demonstrated to have the capability to produce reliable and useful analyses, improper use of the software can cause the results of the analysis to be misleading or inconsistent with the data. As with any complex environmental DSS product, the quality of the output is directly dependent on the skill of the operator.

As with any technology selection, the user must determine if this technology is appropriate for the application and the project data quality objectives. For more information on this and other verified technologies visit the ETV Web site at <http://www.epa.gov/etv>.

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Environmental Technology Verification Report

Environmental Decision Support Software

C Tech Development Corporation

Environmental Visualization System Pro (EVS-PRO)

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Notice

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Foreword

The U.S. Environmental Protection Agency (EPA) is charged by Congress with protecting the nation's natural resources. The National Exposure Research Laboratory (NERL) is EPA's center for the investigation of technical and management approaches for identifying and quantifying risks to human health and the environment. NERL's research goals are to (1) develop and evaluate technologies for the characterization and monitoring of air, soil, and water; (2) support regulatory and policy decisions; and (3) provide the science support needed to ensure effective implementation of environmental regulations and strategies.

EPA created the Environmental Technology Verification (ETV) Program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. The ETV Program is intended to assist and inform those involved in the design, distribution, permitting, and purchase of environmental technologies. This program is administered by NERL's Environmental Sciences Division in Las Vegas, Nevada.

The U.S. Department of Energy's (DOE's) Environmental Management (EM) program has entered into active partnership with EPA, providing cooperative technical management and funding support. DOE EM realizes that its goals for rapid and cost-effective cleanup hinge on the deployment of innovative environmental characterization and monitoring technologies. To this end, DOE EM shares the goals and objectives of the ETV.

Candidate technologies for these programs originate from the private sector and must be commercially ready. Through the ETV Program, developers are given the opportunity to conduct rigorous demonstrations of their technologies under realistic field conditions. By completing the evaluation and distributing the results, EPA establishes a baseline for acceptance and use of these technologies.

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Abbreviations and Acronyms

As	arsenic
.avi	file format for animation visualizations in Windows
.bmp	bitmap (file format)
BNL	Brookhaven National Laboratory
CAD	computer-aided design
CTC	carbon tetrachloride
Cd	cadmium
CD	compact disk
CD-ROM	compact disk—read-only memory
Cr	chromium
DBCP	dibromochloropropane
.dbf	database file
DCA	dichloroethane
DCE	dichloroethene
DCP	dichloropropane
DOE	U.S. Department of Energy
DSS	decision support software
.dxf	data exchange format (file)
EDB	ethylene dibromide
EM	Environmental Management
EPA	U.S. Environmental Protection Agency
ESRI	Environmental Systems Research Institute
EVS	Environmental Visualization System
EVS-PRO	Environmental Visualization System Pro
ETV	Environmental Technology Verification Program
FTP	file transfer protocol
GB	gigabyte
Geo-EAS	Geostatistical Environmental Assessment Software
GIS	geographical information system
GSLIB	Geostatistical Software Library Version 2.0
GUI	graphical user interface
.hav	file format for animation visualizations
IDW	inverse distance weighting
.jpg	JPEG file interchange format
L	liter
MAS	Modeling Animation System
MB	megabyte
MHz	megahertz (used to define the clock speed on computer processors)
MSL	mean sea level
MVS	Mining Visualization System
.mpg	file format for animation visualizations
NAMP	National Analytical Management Program (DOE)
NAPL	nonaqueous phase liquid
NERL	National Exposure Research Laboratory (EPA)
NMERI	New Mexico Engineering Research Institute
ODBC	open database connectivity
ORD	Office of Research and Development
ORNL	Oak Ridge National Laboratory
PCE	perchloroethene or tetrachloroethene
ppb	parts per billion

ppm	parts per million
QA	quality assurance
QC	quality control
RAM	random access memory
ROM	read only memory
SADA	Spatial Analysis and Decision Assistance
SCMT	Site Characterization and Monitoring Technology
.shp	Shape file
TCA	trichloroethane
TCE	trichloroethene
Tc-99	technetium-99
VC	vinyl chloride
VOC	volatile organic compound
VRML	virtual reality modeling language
.wrl	file extension for files created using VRML
2-D	two-dimensional
3-D	three-dimensional

Section 1 — Introduction

Background

The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification Program (ETV) to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV Program is to further environmental protection by substantially accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the design, distribution, financing, permitting, purchase, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations and stakeholder groups consisting of regulators, buyers, and vendor organizations, with the full participation of individual technology developers. The program evaluates the performance of innovative technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests (as appropriate), collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance (QA) protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

ETV is a voluntary program that seeks to provide objective performance information to all of the actors in the environmental marketplace and to assist them in making informed technology decisions. ETV does not rank technologies or compare their performance, label or list technologies as acceptable or unacceptable, seek to determine “best available technology,” nor approve or disapprove technologies. The program does not evaluate technologies at the bench or pilot scale and does not conduct or support research.

The program now operates 12 pilots covering a broad range of environmental areas. ETV has begun with a 5-year pilot phase (1995–2000) to test a wide range of partner and procedural alternatives in various pilot areas, as well as the true market demand for and response to such a program. In these

pilots, EPA utilizes the expertise of partner “verification organizations” to design efficient processes for conducting performance tests of innovative technologies. These expert partners are both public and private organizations, including federal laboratories, states, industry consortia, and private sector facilities. Verification organizations oversee and report verification activities based on testing and QA protocols developed with input from all major stakeholder/customer groups associated with the technology area. The demonstration described in this report was administered by the Site Characterization and Monitoring Technology (SCMT) Pilot. (To learn more about ETV, visit ETV’s Web site at <http://www.epa.gov/etv>.)

The SCMT pilot is administered by EPA’s National Exposure Research Laboratory (NERL). With the support of the U.S. Department of Energy’s (DOE’s) Environmental Management (EM) program, NERL selected a team from Brookhaven National Laboratory (BNL) and Oak Ridge National Laboratory (ORNL) to perform the verification of environmental decision support software. Decision support software (DSS) is designed to integrate measured or modeled data (such as soil or groundwater contamination levels) into a framework that can be used for decision-making purposes. There are many potential ways to use such software, including visualization of the nature and extent of contamination, locating optimum future samples, assessing costs of cleanup versus benefits obtained, or estimating human health or ecological risks. The primary objective of this demonstration was to conduct an independent evaluation of each software’s capability to evaluate three common endpoints of environmental remediation problems: visualization, sample optimization, and cost-benefit analysis. These endpoints were defined as follows.

- *Visualization* — using the software to organize and display site and contamination data in ways that promote understanding of current conditions, problems, potential solutions, and eventual cleanup choices;
- *Sample optimization* — selecting the minimum number of samples needed to define a contaminated area within a predetermined statistical confidence;

- *Cost-benefit analysis* — assessment of either the size of the zone to be remediated according to cleanup goals, or estimation of human health risks due to the contaminants. These can be related to costs of cleanup.

The developers were permitted to select the endpoints that they wished to demonstrate because each piece of software had unique features and focused on different aspects of the three endpoints. Some focused entirely on visualization and did not attempt sample optimization or cost-benefit analysis, while others focused on the technical aspects of generating cost-benefit or sample-optimization analysis, with a minor emphasis on visualization. The evaluation of the DSS focused only on the analyses conducted during the demonstration. No penalty was assessed for performing only part of the problem (e.g., performing only visualization).

Evaluation of a software package that is used for complex environmental problems is by necessity primarily qualitative in nature. It is not meaningful to quantitatively evaluate how well predictions match at locations where data has not been collected. (This is discussed in more detail in Appendix B.) In addition, the selection of a software product for a particular application relies heavily on the user's background, personal preferences (for instance, some people prefer Microsoft Word, while others prefer Corel WordPerfect for word processing), and the intended use of the software (for example, spreadsheets can be used for managing data; however, programs specifically designed for database management would be a better choice for this type of application). The objective of these reports is to provide sufficient information to judge whether the DSS product has the analysis capabilities and features that will be useful for the types of problems typically encountered by the reader.

Demonstration Overview

In September 1998, a demonstration was conducted to verify the performance of five environmental software programs: Environmental Visualizations System (C Tech Development Corp.), ArcView and associated software extenders [Environmental Systems Research Institute (ESRI)], GroundwaterFX (DecisionFX Corp.), SamplingFX (DecisionFX Corp.), and SitePro (Environmental Software Corp.). In October, a sixth software package from the University of Tennessee Research Corporation,

Spatial Analysis and Decision Assistance (SADA), was tested. This report contains the evaluation for Environmental Visualization System (EVS-PRO).

Each developer was asked to use its own software to address a minimum of three test problems. In preparation for the demonstration, ten sites were identified as having data sets that might provide useful test cases for the demonstration. All of this data received a quality control review to screen out sites that did not have adequate data sets. After the review, ten test problems were developed from field data at six different sites. Each site was given a unique identifier (Sites A, B, D, N, S, and T). Each test problem focused on different aspects of environmental remediation problems. From the complete data sets, test problems that were subsets of the entire data set were prepared. The demonstration technical team performed an independent analysis of each of the ten test problems to ensure that the data sets were complete.

All developers were required to choose either Site S or Site N as one of their three problems because these sites had the most data available for developing a quantitative evaluation of DSS performance.

Each DSS was evaluated on its own merits based on the evaluation criteria presented in Section 3. Because of the inherent variability in soil and subsurface contamination, most of the evaluation criteria are qualitative. Even when a direct comparison is made between the developer's analysis and the baseline analysis, different numerical algorithms and assumptions used to interpolate data between measured values at known locations make it almost impossible to make a quantitative judgement as to which technical approach is superior. The comparisons, however, do permit an evaluation of whether the analysis is consistent with the data supplied for the analysis and therefore useful in supporting remediation decisions.

Summary of Analysis Performed by EVS-PRO

C Tech's Environmental Visualization System (EVS-PRO) unites interpolation, geostatistical analysis, and fully three-dimensional (3-D) visualization tools into a software system developed to address, among other things, sample optimization, and cost-benefit analysis. EVS-PRO's capabilities can be used to provide 3-D maps of geologic

structure, subsurface contamination, and regions containing contamination above specified threshold levels at a fixed probability level. EVS-PRO can also perform geostatistical analyses that suggest optimal sample locations for site characterization and can estimate volumes and mass of contaminated media for use in cost-benefit analysis. EVS-PRO can quantify the statistical variation in the contaminant volume and mass estimates resulting from the current extent of characterization

C Tech Development Corporation staff chose to use EVS-PRO to perform the visualization endpoint on selected data from each of the six sites. In addition, sample optimization was performed for the Site B, N, and S problems, making use of the geostatistical algorithms in EVS-PRO. Cost-benefit analysis (estimates of contaminated volume as a function of cleanup level) was also performed on these three problems and for the Site A cost-benefit problem and the Site D sample optimization problem.

The Site A problem was a 3-D groundwater contamination cost-benefit problem. The data supplied included maps of buildings, roads, and water bodies; groundwater contamination concentrations for more than 50 wells, with data supplied at 5-ft vertical intervals for each well; the hydraulic head in each well; and information on the elevation of the ground surface and bedrock at each well. The contaminants of concern were perchloroethene (PCE) and trichloroethane (TCA). EVS-PRO generated 3-D maps of the regions of contamination above two threshold concentrations at three probability levels. A scale of coordinates and surface features were included on the maps to provide a frame of reference. EVS-PRO also generated a 3-D animation depicting the extent of contamination. The animation rotated the viewing angle of the contamination through 360° to provide the analyst with a more complete view of the contamination. In addition, EVS-PRO was used to estimate the volume of contamination at the three probability levels and two threshold concentrations.

The Site B sample optimization problem involved groundwater contamination in two spatial dimensions. The data supplied included an aerial photograph of the site; maps of buildings, roads, and water bodies; groundwater contamination concentrations at 25 well locations; and the hydraulic head in each well. The C Tech analyst used the geostatistical algorithms in EVS-PRO to

identify 23 additional locations for further sampling to define the extent of contamination for technetium-99 (Tc-99). On the basis of the final data set, the analyst used EVS-PRO to generate maps of the plume at the two threshold concentrations at three probability levels. The software depicted measured concentrations at the correct spatial locations with color-coded spheres; the color represented the concentration value. A scale of coordinates and surface features was included on the maps to provide a frame of reference. Some maps superimposed the aerial photograph to provide a frame of reference. A similar analysis was performed for the other two contaminants, trichloroethene (TCE) and vinyl chloride (VC), using the original data set (i.e., sample optimization was not performed). The analyst also provided EVS-PRO-generated virtual reality modeling language (VRML) files that could be viewed and navigated with free downloadable plug-ins for an Internet browser. (C Tech recommends the Cosmo Viewer that can be obtained from www.karmanaut.com/cosmo/player.) Navigation permits the viewer to rotate the drawing to any angle to better understand the extent of contamination. The data were also used to generate a cost-benefit analysis of the volume contaminated vs cleanup threshold for all three contaminants.

The Site D sample optimization problem involved groundwater contamination from four organic compounds—dichloroethane (DCA), dichloroethene (DCE), PCE, and TCE. The data supplied included maps of buildings, roads, and water bodies; boring data providing geologic structure; groundwater contamination concentrations at 33 well locations for five sampling periods; and the hydraulic head in each well during one sampling period. The EVS-PRO scripting language was used to create a routine to query the data file, select the data for a single contaminant and sampling time, and visualize the contaminant data, producing 2-D and 3-D maps of contamination. The process was repeated automatically for each contaminant at each sampling period. The 2-D maps provided a top view of the areal extent of contamination with a site map containing buildings and roads. The 3-D maps showed the contamination as a function of depth, with solid and exploded views. The exploded views helped make clear the extent of contamination in different geologic layers. EVS-PRO also provided estimates of the volume of contaminated water above the specific threshold concentration for each contaminant.

The Site N sample optimization problem involved soil contamination from three heavy metals—arsenic (As), cadmium (Cd), and chromium (Cr). EVS-PRO was used to perform sample optimization for arsenic contamination. The analysts used the software in an iterative fashion to select a few sample locations for further data collection. This new information was used to generate the next set of sample locations, and the process continued until the maximum number of allowed sample locations (80 in this problem) had been specified. With the final data set, EVS-PRO generated arsenic concentration contour maps based on contaminant threshold concentrations and the degree of confidence in the interpolation results. These maps were overlain with site features (roads and waterways). Maps of uncertainty as a function of the number of samples were also provided to illustrate the reduction in uncertainty obtained with increased sampling.

The Site S sample optimization problem is a 3-D groundwater contamination problem for a single contaminant [carbon tetrachloride (CTC)]. Initially, concentration data were supplied for 19 well locations at 5-ft vertical intervals within each well and for another 5 well locations at 40-ft vertical intervals. Using the geostatistical routines in EVS-PRO to select sample locations, the C Tech analyst requested additional data at 15 locations to further define the plume. EVS-PRO was then used to generate 2-D maps of the concentration distribution based on the maximum concentration in each well and the probability of exceeding the two threshold concentrations for CTC. Three-dimensional visualizations were also provided in VRML format to allow the user to navigate around the plume. The

data were also used to generate a cost-benefit analysis of the contaminated volume vs the cleanup threshold.

The Site T problem was a groundwater contamination problem. The data supplied for analysis of this problem included maps of buildings and roads, soil and groundwater contamination data for four organic contaminants, and geologic boring data representing the location of different soil layers (e.g., clay, sand, silt). The C Tech analyst chose to demonstrate the capability of the software to visualize the 3-D subsurface soil layer structure. A 3-D animation that rotated the viewing angle of the soil structure through 360° was provided to permit a more complete view of the layers.

Section 2 of this report contains a brief description of the capabilities of EVS-PRO. Section 3 outlines the process followed in conducting the demonstration. This section discusses the approach used to develop the test problems, the ten test problems, the baseline analyses that were used for comparison with the developers' analyses, and the evaluation criteria. More detailed descriptions of the test problems can be found in Appendix A. Section 4 presents the technical review of the analyses performed by EVS-PRO. It includes a more detailed discussion of the problems attempted, comparisons of the EVS-PRO analyses and the baseline results, and an evaluation of EVS-PRO against the criteria established in Section 3. Section 5 presents an update on the EVS technology and provides examples of representative applications of EVS in environmental problem-solving.

Section 2 — Environmental Visualization System Capabilities

This section provides a general overview of the capabilities of the products in C Tech's Environmental Visualization System (EVS). The information was supplied by C Tech.

EVS-PRO Features

C Tech's EVS-PRO unites interpolation, geologic modeling, geostatistical analysis, and fully 3-D visualization tools into a software system developed to address mining and environmental contamination issues. EVS-PRO can be used to analyze all types of analytes and geophysical data in any environment (soil, groundwater, surface water, air, etc.). One of EVS-PRO's greatest strengths is its integrated geostatistical analysis, which provides quantitative assessment of the quality of a site assessment ("Min-Max Plume" technology); as a part of the geostatistical analysis additional sample locations requiring investigation are identified. The tools that are part of the software can improve site assessment and enhance the capability to analyze and present data for assessments, remediation planning, litigation support, regulatory reporting, and public relations.

EVS-PRO was developed to meet the needs of the geologist, the environmental engineer, and the environmental program manager as they relate to the following areas:

- *Site assessment:* Determination of optimal locations for collecting data in order to best determine the spatial extent of contamination at the lowest possible cost.
- *Site evaluation:* Determination of the spatial extent of contamination. EVS-PRO's "Min-Max Plume" technology quantifies the statistical variation in the volume and mass estimates resulting from the current level of characterization.
- *Geology:* Creation of a 3-D model of the geology of a site and determination of the relationship between the geology and the contaminant plumes. This information allows for better-targeted remediation plans that consider the effect of geology on the migration and capture of contamination. EVS-PRO can also

compute plume volumes and masses on a (geologic) layer basis.

- *Communication:* Visual presentation of site geology and contamination is critical for effective communication. EVS-PRO can integrate geologic information, environmental contamination data, site maps (showing buildings, roads, and other features), and aerial photographs into a single visualization. EVS-PRO provides both still and animated 3-D visualization.

EVS-PRO is a modular software system designed to address the wide range of problems encountered by the environmental community. It can be customized for the most demanding application while preserving an ease of use that provides immediate productivity. EVS-PRO can deal with virtually all types of data and environments. It is designed to be easy enough for use (at a rudimentary level) by nonspecialist personnel. However, the modular software architecture and the breadth of its tools provide comprehensive capabilities that can meet the needs of scientists and researchers. For example, at a site with a history of multiyear sampling, a script can be generated to sort and query the data and plot contamination levels from each year, and ultimately to display all of the data in the form of an animation.

EVS-PRO can be used on Windows 95, 98, 2000, and NT systems. It does not require any supplementary software; however, it can interface with many popular software packages. EVS-PRO can read and write AutoCAD .dxf files and ESRI shapefiles and can directly access ODBC-compliant databases, provided ODBC 32 is installed on the client's computer. Environmental database and data management software products such as ESRI's ArcView GIS, Integrate's TerraBase, EarthSoft's EQUIS, and GIS Solution's GIS/Key also support output to EVS-PRO. EVS-PRO can perform 3-D postprocessing and animation for groundwater and solute transport modeling packages such as MODFLOW and MT3D by using a recently released translation module that converts standard MODFLOW and MT3D output files to EVS-PRO format.

Overview of C Tech Environmental Software

C Tech Development Corporation has five major products. EVS-PRO was used in this demonstration. These products, the single-license price, and a brief description of each software follow.

- EVS for ArcView** (Environmental Visualization System for ArcView) — \$2,495
 EVS for ArcView is a subset of EVS Standard, described below. It is tightly integrated with ArcView through a powerful ArcView extension. It has 15 applications that include geology only, chemistry only and geology and chemistry applications. It is fully 3-D and has the same viewer as C Tech’s other products. EVS for ArcView is a low-cost way to add more 3-D capability to an office: EVS for ArcView seats may be combined with EVS-PRO or MVS seats that are reserved for the more expert users. EVS for ArcView was designed to be used by nearly anyone with a background in environmental problems, including project managers and principals.
- MAS** (Modeling Animation System) — \$2,495
 MAS has a limited subset of the animation capabilities of EVS-PRO and a full suite of visualization modules. It does not include any geostatistics modules or any of the geologic modeling or gridding capabilities of EVS-PRO. MAS was developed to perform 3-D postprocessing and animation for groundwater and solute transport modeling packages such as MODFLOW, MT3D, and CFEST.
- EVS Standard** (Environmental Visualization System Standard) — \$4,995

EVS Standard is C Tech’s baseline customizable 3-D analysis and visualization system. EVS Standard includes all of the capabilities of EVS for ArcView (including ArcView GIS integration) and adds a modular, customizable environment for geologists and environmental engineers.

- EVS-PRO** (Environmental Visualization System Pro) — \$9,995
 EVS-PRO is C Tech’s most popular product for state-of-the art analysis, visualization, and animation. EVS-PRO builds upon all of the capabilities of EVS Standard and MAS and adds advanced gridding, model building, output options, geostatistics capabilities, animation, and GIS functions to accommodate litigation support, public relations and the more demanding requirements of earth science professionals.
- MVS** (Mining Visualization System) — \$24,995
 Mining Visualization System (MVS) is C Tech’s flagship product for state-of-the art analysis and visualization. MVS builds upon all of the capabilities of EVS-PRO and adds powerful new features targeted to the needs of mining engineers and planners, or the geologist or environmental engineer with the most demanding requirements.

In addition to the fixed license product, EVS-PRO and MVS can be bought with a floating license. The floating license versions have steep discounts with quantity and a more complex pricing structure. The floating license uses a hardware key on the machine that serves licenses, but any machine on the network can run the software until the available seats are used up. Table 1 provides prices for six nominal

Table 1. Pricing structure for floating-license version of EVS-PRO

Tier class	Nominal seats	Price for first seat	Additional seats	Price for nominal number of seats	Effective seat price for nominal seats
A	1	\$13,500	\$6,250	\$13,500 for 1 seat	\$13,500
B	3	\$16,000	\$4,000	\$24,000 for 3 seats	\$8,000
C	8	\$23,000	\$3,000	\$44,000 for 8 seats	\$5,500
D	17	\$41,800	\$1,800	\$70,600 for 17 seats	\$4,153
E	34	\$51,500	\$1,500	\$101,000 for 34 seats	\$2,971
F	100	\$101,000	\$1,000	\$200,000 for 100 seats	\$2,000

configurations; prices for other configurations are available on request.

One year of technical support, with software maintenance and upgrades, is included in the

purchase. Additional years are currently 12% of software's list price. Training courses are available, and extensive documentation is available online, through the Web, and in a users' manual. Tutorials are provided with the software to help train users.

Section 3 — Demonstration Process and Design

Introduction

The objective of this demonstration was to conduct an independent evaluation of the capabilities of several DSSs in the following areas: (1) effectiveness in integrating data and models to produce information that supports decisions pertaining to environmental contamination problems, and (2) the information and approach used to support the analysis. Specifically, three endpoints were evaluated:

- *Visualization* — Visualization software was evaluated in terms of its ability to integrate site and contamination data in a coherent and accurate fashion that aids in understanding the contamination problem. Tools used in visualization can range from data display in graphical or contour form to integrating site maps and aerial photos into the results.
- *Sample optimization* — Sample optimization was evaluated for soil and groundwater contamination problems in terms of the software's ability to select the minimum number of samples needed to define a contaminated region with a specified level of confidence.
- *Cost-benefit analysis* — Cost-benefit analysis involved either defining the size of remediation zone as a function of the cleanup goal or evaluating the potential human health risk. For problems that defined the contamination zone, the cost could be evaluated in terms of the size of the zone, and cost-benefit analysis could be performed for different cleanup levels or different statistical confidence levels. For problems that calculated human health risk, the cost-benefit calculation would require computing the cost to remediate the contamination as a function of reduction in health risk.

Secondary evaluation objectives for this demonstration were to examine the reliability, resource requirements, range of applicability, and ease of operation of the DSS. The developers participated in this demonstration in order to highlight the range and utility of their software in addressing the three endpoints discussed above.

Actual users might achieve results that are less reliable, as reliable, or more reliable than those achieved in this demonstration, depending on their expertise in using the software to solve environmental problems.

Development of Test Problems

Test Problem Definition

A problem development team was formed to collect, prepare, and conduct the baseline analysis of the data. A large effort was initiated to collect data sets from actual sites with an extensive data collection history. Through literature review and contact with different government agencies (EPA field offices, DOE, the U.S. Department of Defense, and the U.S. Geological Survey) the team identified ten sites throughout the United States that had the potential for developing test problems for the demonstration. The data from these ten sites were screened for completeness of data, range of environmental conditions covered, and potential for developing challenging and defensible test problems for the three endpoints of the demonstration. The objective of the screening was to obtain a set of problems that covered a wide range of contaminants (metals, organics, and radionuclides), site conditions, and source conditions (spills, continual slow release, and multiple releases over time). On the basis of this screening, six sites were selected for development of test problems. Of these six sites, four had sufficient information to provide multiple test problems. This provided a total of ten test problems for use in the demonstration.

Summary of Test Problems

A detailed description of the ten test problems was supplied to the developers as part of the demonstration (Sullivan, Armstrong, and Osleeb 1998). A general description of each of the problems can be found in Appendix A. This description includes the operating history of the site, the contaminants of concern, and the objectives of the test problem (e.g., define the volume over which the contaminant concentration exceeds 100 µg/L). The test problems analyzed by C Tech are discussed in Section 4 as part of the evaluation of the performance of EVS-PRO.

Table 2 summarizes the ten problems by site identifier, location of contamination (soil or groundwater), problem endpoints, and contaminants of concern. The visualization endpoint could be performed on all ten problems. In addition, there were four sample optimization problems, four cost-benefit problems, and two problems that combined sample optimization and cost-benefit issues. The contaminants included metals, volatile organic compounds (VOCs), and radionuclides. The environmental conditions included 2-D and 3-D soil and groundwater contamination problems over varying geologic, hydrologic, and environmental settings. Table 3 provides a summary of the types of data supplied with each problem.

Analysis of Test Problems

Prior to the demonstration, the demonstration technical team performed a quality control examination of all data sets and test problems. This involved reviewing database files for improper data (e.g., negative concentrations), removing information that was not necessary for the demonstration (e.g., site descriptors), and limiting the data to the contaminants, the region of the site, and the time frame covered by the test problems (e.g., only data from one year for three contaminants). For sample optimization problems, a limited data set was prepared for the developers as a starting point for the analysis. The remainder of the

Table 2. Summary of test problems

Site identifier	Media	Problem endpoints	Contaminants
A	Groundwater	Visualization, sample optimization	Dichloroethene, trichloroethene
A	Groundwater	Visualization, cost-benefit	Perchloroethene, trichloroethane
B	Groundwater	Visualization, sample optimization, cost-benefit	Trichloroethene, vinyl-chloride, technetium-99
D	Groundwater	Visualization, sample optimization, cost-benefit	Dichloroethene, dichloroethane, trichloroethene, perchloroethene
N	Soil	Visualization, sample optimization	Arsenic, cadmium, chromium
N	Soil	Visualization, cost-benefit	Arsenic, cadmium, chromium
S	Groundwater	Visualization, sample optimization	Carbon tetrachloride
S	Groundwater	Visualization, cost-benefit	Chlordane
T	Soil	Visualization, sample optimization	Ethylene dibromide, dibromochloropropane, dichloropropane, carbon tetrachloride
T	Groundwater	Visualization, cost-benefit	Ethylene dibromide, dibromochloropropane, dichloropropane, carbon tetrachloride

Table 3. Data supplied for the test problems

Site history	Industrial operations, environmental settings, site descriptions
Surface structure	Road and building locations, topography, aerial photos
Sample locations	x, y, z coordinates for soil surface samples soil borings groundwater wells
Contaminants	Concentration data as a function of time and location (x, y, and z) for metals, inorganics, organics, radioactive contaminants
Geology	Soil boring profiles, bedrock stratigraphy
Hydrogeology	Hydraulic conductivities in each stratigraphic unit; hydraulic head measurements and locations
Transport parameters	Sorption coefficient (K_d), biodegradation rates, dispersion coefficients, porosity, bulk density
Human health risk	Exposure pathways and parameters, receptor location

data were reserved to provide input concentrations to developers for their sample optimization analysis.

For cost-benefit problems, the analysts were provided with an extensive data set for each test problem with a few data points reserved for checking the DSS analysis. The data quality review also involved importing all graphics files (e.g., .dxf and .bmp) that contained information on surface structures such as buildings, roads, and water bodies to ensure that they were readable and useful for problem development. Many of the drawing files were prepared as ESRI shape files compatible with ArcView™. ArcView was also used to examine the graphics files.

Once the quality control evaluation was completed, the test problems were developed. The test problems were designed to be manageable within the time frame of the demonstration and were often a subset of the total data set. For example, in some cases, test problems were developed for a selected region of the site. In other cases, the database could have contained information for tens of contaminants, while the test problems themselves were limited to the three or four principal contaminants. At some sites, data were available over time periods exceeding 10 years. For the DSS test problems, the analysts were typically supplied chemical and hydrologic data for a few sampling periods.

Once the test problems were developed, the demonstration technical team conducted a complete analysis of each test problem. These analyses served as the baseline for evaluating results from the developers. Each analysis consisted of taking the entire data set and obtaining an estimate of the plume boundaries for the specified threshold contaminant concentrations and estimating the area of contamination above the specified thresholds for each contaminant.

The independent data analysis was performed using Surfer™ (Golden Software 1996). Surfer was selected for the task because it is a widely used, commercially available software package with the functional capabilities necessary to examine the data. This functional capability includes the ability to import drawing files to use as layers in the map, and the ability to interpolate data in two dimensions. Surfer has eight different interpolation methods, each of which can be customized by changing model parameters, to generate contours. These different contouring options were used to generate multiple

views of the interpolated regions of contamination and hydrologic information. The best fit to the data was used as the baseline analysis. For 3-D problems, the data were grouped by elevation to provide a series of 2-D slices of the problem. The distance between slices ranged between 5 and 10 ft depending on the availability of data. Compilation of vertical slices generated 3-D depictions of the data sets. Comparisons of the baseline analysis to the EVS-PRO results are presented in Section 4.

In addition to Surfer, two other software packages were used to provide an independent analysis of the data and to provide an alternative representation for comparison with the Surfer results. The Geostatistical Software Library Version 2.0 (GSLIB) and Geostatistical Environmental Assessment Software Version 1.1 (Geo-EAS) were selected because both provide enhanced geostatistical routines that assist in data exploration and selection of modeling parameters to provide extensive evaluations of the data from a spatial context (Deutsch and Journel 1992; Englund and Sparks 1991). These three analyses provide multiple lines of reasoning, particularly for the test problems that involved geostatistics. The results from Surfer, GSLIB, and Geo-EAS were compared and contrasted to determine the best fit of the data, thus providing a more robust baseline analysis for comparison to the developers' results.

Under actual site conditions, uncertainties and natural variability make it impossible to define plume boundaries exactly. In these case studies, the baseline analyses serve as a guideline for evaluating the accuracy of the analyses prepared by the developers. Reasonable agreement should be obtained between the baseline and the developer's results. A discussion of the technical approaches and limitations to estimating physical properties at locations that are between data collection points is provided in Appendix B.

To minimize problems in evaluating the software associated with uncertainties in the data, the developers were required to perform an analysis of one problem from either Site N or Site S. For Site N, with over 4000 soil contamination data points, the baseline analysis reflected the actual site conditions closely; and if the developers performed an accurate analysis, the correlation between the two should be high. For Site S, the test problems used actual contamination data as the basis for developing a problem with a known solution. In both Site S

problems, the data were modified to simulate a constant source term to the aquifer in which the movement of the contaminant can be described by the classic advective-dispersive transport equation. Transport parameters were based on the actual data. These assumptions permitted release to the aquifer and subsequent transport to be represented by a partial differential equation that was solved analytically. This analytical solution could be used to determine the concentration at any point in the aquifer at any time. Therefore, the developer's results can be compared against calculated concentrations with known accuracy.

After completion of the development of the ten test problems, a predemonstration test was conducted. In the predemonstration, the developers were supplied with a problem taken from Site D that was similar to test problems for the demonstration. The objective of the predemonstration was to provide the developers with a sample problem with the level of complexity envisioned for the demonstration. In addition, the predemonstration allowed the developers to process data from a typical problem in advance of the demonstration and allowed the demonstration technical team to determine if any problems occurred during data transfer or because of problem definition. The results of the predemonstration were used to refine the problems used in the demonstration.

Preparation of Demonstration Plan

In conjunction with the development of the test problems, a demonstration plan (Sullivan and Armstrong 1998) was prepared to ensure that all aspects of the demonstration were documented and scientifically sound and that operational procedures were conducted within quality assurance (QA)/quality control (QC) specifications. The demonstration plan covered

- the roles and responsibilities of demonstration participants;
- the procedures governing demonstration activities such as data collection to define test problems and data preparation, analysis, and interpretation;
- the experimental design of the demonstration;
- the evaluation criteria against which the DSS would be judged; and
- QA and QC procedures for conducting the demonstration and for assessing the quality of the information generated from the demonstration.

All parties involved with implementation of the plan approved and signed the demonstration plan prior to the start of the demonstration.

Summary of Demonstration

Activities

On September 14–25, 1998, the Site Characterization and Monitoring Technology Pilot, in cooperation with DOE's National Analytical Management Program, conducted a demonstration to verify the performance of five environmental DSS packages. The demonstration was conducted at the New Mexico Engineering Research Institute, Albuquerque, New Mexico. An additional software package was tested on October 26–29, 1998, at Brookhaven National Laboratory, Upton, New York.

The first morning of the demonstration was devoted to a brief presentation of the ten test problems, a discussion of the output requirements to be provided from the developers for evaluation, and transferring the data to the developers. The data from all ten test problems—along with a narrative that provided a description of the each site, the problems to be solved, the names of data files, structure of the data files, and a list of output requirements—were given to the developers. The developers were asked to address a minimum of three test problems for each software product.

Upon completion of the review of the ten test problems and the discussion of the outputs required from the developers, the developers received data sets for the problems by file transfer protocol (FTP) from a remote server or on a high-capacity removable disk. Developers downloaded the data sets to their own personal computers, which they had supplied for the demonstration. Once the data transfers of the test problems were complete and the technical team had verified that each developer had received the data sets intact, the developers were allowed to proceed with the analysis at their own pace. During the demonstration, the technical team observed the developers, answered questions, and provided data as requested by the developers for the sample optimization test problems. The developers were given 2 weeks to complete the analysis for the test problems that they selected.

The third day of the demonstration was visitors' day, an open house during which people interested in DSS could learn about the various products being tested. During the morning of visitors' day,

presenters from EPA, DOE, and the demonstration technical team outlined the format and content of the demonstration. This was followed by a presentation from the developers on the capabilities of their respective software products. In the afternoon, attendees were free to meet with the developers for a demonstration of the software products and further discussion.

Prior to leaving the test facility, the developers were required to provide the demonstration technical team with the final output files generated by their software. These output files were transferred by FTP to an anonymous server or copied to a zip drive or compact disk-read only memory (CD-ROM). The technical team verified that all files generated by the developers during the demonstration were provided and intact. The developers were given a 10-day period after the demonstration to provide a written narrative of the work that was performed and a discussion of their results.

Evaluation Criteria

One important objective of DSS is to integrate data and models to produce information that supports an environmental decision. Therefore, the overriding performance goal in this demonstration was to provide a credible analysis. The credibility of a software and computer analysis is built on four components:

- good data,
- adequate and reliable software,
- adequate conceptualization of the site, and
- well-executed problem analysis (van der Heijde and Kanzer 1997).

In this demonstration, substantial efforts were taken to evaluate the data and remove data of poor quality prior to presenting it to the developers. Therefore, the developers were directed to assume that the data were of good quality. The technical team provided the developers with detailed site maps and test problem instructions on the requested analysis and assisted in site conceptualization. Thus, the demonstration was primarily to test the adequacy of the software and the skills of the analyst. The developers operated their own software on their own computers throughout the demonstration.

Attempting to define and measure credibility makes this demonstration far different from most demonstrations in the ETV program in which measurement devices are evaluated. In the typical ETV demonstrations, quality can be measured in a quantitative and statistical manner. This is not true for DSS. While there are some quantitative measures, there are also many qualitative measures. The criteria for evaluating the DSS's ability to support a credible analysis are discussed below. In addition a number of secondary objectives, also discussed below, were used to evaluate the software. These included documentation of software, training and technical support, ease of use of the software, efficiency, and range of applicability.

Criteria for Assessing Decision Support

The developers were asked to use their software to answer questions pertaining to environmental contamination problems. For visualization tools, integration of geologic data, contaminant data, and site maps to define the contamination region at specified concentrations was requested. For software tools that address sample optimization questions, the developers were asked to suggest optimum sampling locations, subject to constraints on the number of samples or on the confidence with which contamination concentrations were known. For software tools that address cost-benefit problems, the developers were asked either to define the volume (or area) of contamination and, if possible, supply the statistical confidence with which the estimate was made, or to estimate human health risks resulting from exposure to the contamination.

The criterion for evaluation was the credibility of the analyses to support the decision. This evaluation was based on several points, including

- documentation of the use of the models, input parameters, and assumptions;
- presentation of the results in a clear and consistent manner;
- comparison of model results with the data and baseline analyses;
- evaluation of the use of the models; and
- use of multiple lines of reasoning to support the decision.

The following sections provide more detail on each of these topics.

Documentation of the Analysis and Evaluation of the Technical Approach

The developers were requested to supply a concise description of the objectives of the analysis, the procedures used in the analysis, the conclusions of the analysis with technical justification of the conclusions, and a graphical display of the results of the analysis. Documentation of key input parameters and modeling assumptions was also requested. Guidance was provided on the quantity and type of information requested to perform the evaluation.

Based on observations obtained during the demonstration and the documentation supplied by the developers, the use of the models was evaluated and compared to standard practices. Issues in proper use of the models include selection of appropriate contouring parameters, spatial and temporal discretization, solution techniques, and parameter selection.

This evaluation was performed as a QA check to determine if standard practices were followed. This evaluation was useful in determining whether the cause of discrepancies between model projections and the data resulted from operator actions or from the model itself and was instrumental in understanding the role of the operator in obtaining quality results.

Comparison of Projected Results with the Data and Baseline Analysis

Quantitative comparisons between DSS-generated predictions and the data or baseline analyses were performed and evaluated. In addition, DSS-generated estimates of the mass and volume of contamination were compared to the baseline analyses to evaluate the ability of the software to determine the extent of contamination. For visualization and cost-benefit problems, developers were given a detailed data set for the test problem with only a few data points held back for checking the consistency of the analysis. For sample optimization problems, the developers were given a limited data set to begin the problem. In this case, the data not supplied to the developers were used for checking the accuracy of the sample optimization analysis. However, because of the inherent variability in environmental systems and the choice of different models and parameters by the analysts, quantitative measures of the accuracy of the analysis

are difficult to obtain and defend. Therefore, qualitative evaluations of how well the model projections reproduced the trends in the data were also performed.

A major component of the analysis of environmental data sets involves predicting physical or chemical properties (contaminant concentrations, hydraulic head, thickness of a geologic layer, etc.) at locations between measured data. This process, called interpolation, is often critical in developing an understanding of the nature and extent of the environmental problem. The premise of interpolation is that the estimated value of a parameter is a weighted average of measured values around it. Different interpolation routines use different criteria to select the weights. Due to the importance of obtaining estimates of data between measured data points in many fields of science, a wide number of interpolation routines exist. Three classes of interpolation routines commonly used in environmental analysis are nearest neighbor, inverse distance, and kriging. These three classes of interpolation, and their strengths and limitations, are discussed in detail in Appendix B.

Use of Multiple Lines of Reasoning

Environmental decisions are often made with uncertainties because of an incomplete understanding of the problem and lack of information, time, and/or resources. Therefore, multiple lines of reasoning are valuable in obtaining a credible analysis. Multiple lines of reasoning may incorporate statistical analyses, which in addition to providing an answer, provide an estimate of the probability that the answer is correct. Multiple lines of reasoning may also incorporate alternative conceptual models or multiple simulations with different parameter sets. The DSS packages were evaluated on their capabilities to provide multiple lines of reasoning.

Secondary Evaluation Criteria Documentation of Software

The software was evaluated in terms of its documentation. Complete documentation includes detailed instructions on how to use the software package, examples of verification tests performed with the software package, a discussion of all output files generated by the software package, a discussion of how the output files may be used by other programs (e.g., ability to be directly imported into an Excel spreadsheet), and an explanation of the theory

behind the technical approach used in the software package.

Training and Technical Support

The developers were asked to list the necessary background knowledge necessary to successfully operate the software package (i.e., basic understanding of hydrology, geology, geostatistics, etc.) and the auxiliary software used by the software package (e.g., Excel). In addition, the operating systems (e.g., Unix, Windows NT) under which the DSS can be used was requested. A discussion of training, software documentation, and technical support provided by the developers was also required.

Ease of Use

Ease of use is one of the most important factors to users of computer software. Ease of use was evaluated by an examination of the software package's operation and on the basis of adequate on-line help, the availability of technical support, the flexibility to change input parameters and databases used by the software package, and the time required for an experienced user to set up the model and prepare the analysis (that is, input preparation time,

time required to run the simulation, and time required to prepare graphical output). The demonstration technical team observed the operation of each software product during the demonstration to assist in determining the ease of use. These observations documented operation and the technical skills required for operation. In addition, several members of the technical team were given a 4-hour tutorial by each developer on their respective software to gain an understanding of the training level required for software operation as well as the functional capabilities of each software.

Efficiency and Range of Applicability

Efficiency was evaluated on the basis of the resource requirements used to evaluate the test problems. This was assessed through the number of problems completed as a function of time required for the analysis and computing capabilities.

Range of applicability is defined as a measure of the software's ability to represent a wide range of environmental conditions and was evaluated through the range of conditions over which the software was tested and the number of problems analyzed.

Section 4 — EVS-PRO Evaluation

EVS-PRO Technical Approach

For sample optimization and quantification of uncertainties in predicted values, EVS-PRO uses a geostatistical approach. Geostatistical methods are based on the premise that measured variables located close to each other will have similar values, while variables far apart will have little correlation between their corresponding values. A statistical measure for this interrelationship is summarized by the correlation between measured variables measured at different points in space. This measure or related measures such as the variogram and covariance form the central idea around which linear estimation methods in geostatistics operate. The use of correlation measures also separates this estimation method from other interpolation algorithms such as inverse distance, linear interpolation, splines, and quadrature methods. Using a statistical estimator allows the estimation error to be calculated along with the estimate. Thus, a geostatistical method provides both the most likely value and an estimate of the range of other possible values for a given location. This is important information because the spatial variability present in most parameters is such that values predicted prior to actual data measurement are unlikely to exactly match the “newly” measured value. In fact, often there are many possible solutions to the estimation problem that agree with the measurements (Appendix B). Kriging, which is used in EVS-PRO, is one of the more common geostatistical methods used to provide smoothed estimates of variables. The kriging model used in EVS-PRO matches the data at all measured locations.

EVS-PRO imports measured data, defines a grid (i.e., divides the volume of concern into a number of 3-D hexahedral blocks), automatically calculates the spatial correlation of the data in three dimensions (i.e., generates a variogram), and from the variogram estimates the parameters necessary for kriging interpolation of the data. The kriging process provides an estimate of the most likely value of the variable and a statistical measure of the variability expected at that location. Default values for calculating the spatial correlation can be changed by the user of EVS-PRO.

In performing estimates of the volume of soil that contains contamination above the cleanup concentration as a function of probability levels, EVS-PRO uses “Min-Max Plume” technology. In this approach, EVS-PRO determines the minimum and maximum plume volume by using kriging interpolation to calculate the nominal value and associated standard deviation at every location in the model. The predicted nominal value and standard deviation are used to estimate the “minimum” and “maximum” values as a function of probability level. For the case of the maximum plume and a 75% probability level, a “maximum” value is determined at each model location such that if a measurement were collected at any location, the hypothetically measured value could be expected to be less than the “maximum” value 75% of the time. Using interpolation and the “maximum” value at each model location, the volume of contamination is defined at the 75% “maximum” level. The “minimum” value is defined as the value at which the hypothetically measured value is expected to be greater than the “minimum” value 75% of the time, and the 75% “minimum” plume is defined similarly. The 75% “minimum” plume represents the region of contamination in which the analysis shows that there is a 75% probability that the contamination volume is at least that large. This approach of estimating concentration as a function of probability is consistent with the EPA data quality objectives guidance (EPA 1994).

The objective in performing sample optimization is to collect samples at the locations that will provide the maximum amount of information to define the extent of contamination. This is accomplished in EVS-PRO with a measure called uncertainty. For determining sample locations, EVS-PRO first calculates the confidence in the predicted values at each model location. Confidence is a measure of how well the predicted value represents the actual value and answers questions such as, “What is the probability that the predicted value will be within a factor of 10 of the measured value?” Uncertainty, as used in EVS-PRO, is a concentration-weighted inverse of the confidence. This weighting gives more importance in selecting sample locations to regions

of high concentration and low confidence. High uncertainty indicates a high probability of poorly characterized contamination. The weighting function used to compute uncertainty has been optimized with the intent of minimizing the number of new sampling locations.

EVS-PRO permits the user to focus the uncertainty estimates on a specific range of concentration values by setting floor and ceiling values for calculating uncertainty. Values below the floor level are considered unimportant (or more specifically, they are set to the floor level). Similarly, values above the ceiling level are set to the ceiling value. Setting the ceiling at the concentration value of most interest, such as the threshold level, will cause the selection of new sampling locations to converge most rapidly on defining the plume boundary at the ceiling concentration. This will, however, sacrifice the accurate characterization of the most contaminated regions in the domain. This limitation is generally acceptable if the primary goal is determination of the extent (rather than specific distribution) of contamination.

Description of Test Problems

C Tech staff chose to use EVS-PRO to perform the visualization endpoint on selected data from each of the six sites. In addition, the software performed sample optimization for Sites B, N, and S. Cost-benefit analysis (estimates of contaminated volume as a function of cleanup concentrations) was also performed on these three problems and for the Site A cost-benefit problem and the Site D sample optimization problem. As part of the demonstration, several hundred visualization outputs were generated. These included 3-D depictions of plume boundaries with site features superimposed, animations providing multiple perspectives on contamination plumes and subsurface stratigraphy, and interactive 3-D visualizations that allow the viewer to rotate the figure to any viewing angle. A few examples that display the range of capabilities and features in EVS-PRO are included in this report. A general description of each test problem and the analysis performed using EVS-PRO follows. Detailed descriptions of all test problems are provided in Appendix A and in Sullivan, Armstrong, and Osleeb (1998).

Site A Cost-Benefit Problem

The Site A cost-benefit problem was a 3-D groundwater contamination problem for two

contaminants, PCE and TCA. Contamination had migrated more than a mile towards nearby well fields. The objective of this test problem was to define the location, depth, and volume of the plume at PCE concentrations of 100 and 500 µg/L and TCA concentrations of 5 and 50 µg/L at probability levels of 10, 50, and 90%. The 10% probability region is the region in which there is at least a 10% chance that the contamination will exceed the threshold concentration. Therefore, the 10% probability region predicts the maximum volume of contamination and the 90% probability region predicts the minimum. In the terminology of EVS, the 10% probability plume corresponds to the 90% “maximum” plume and the 90% probability region corresponds to the 90% “minimum” plume. The probability of exceeding a threshold concentration is used in a cost-benefit analysis of cleanup goals vs the cost of remediation. C Tech used EVS-PRO to accomplish the problem objectives.

The data supplied for the analysis of Site A included maps of roads, buildings, and water bodies; data on the concentrations of the two contaminants at different depths and locations in more than 80 groundwater wells; hydraulic head data; and data on geologic structure. Chemical analysis data were collected at 5-ft intervals from each well.

Site B Sample Optimization and Cost-Benefit Problem

The Site B problem was a 2-D groundwater contamination problem. Initial sampling attempted to define the central region of the contaminant plume, which extends more than a mile and approaches a nearby river. The objective of the sample optimization problem was to develop a sampling strategy to define the region in which the groundwater contamination exceeds specified threshold concentrations (Table 4) at probability levels of 10, 50, and 90%. In addition, the analyst was asked to calculate the health risks associated

Table 4. Site B groundwater contamination problem threshold concentrations

Contaminant	Threshold concentrations
TCE	50, 500 (µg/L)
VC	50, 250 (µg/L)
Tc-99	10000, 40000 (pCi/L)

with drinking 2 L of contaminated groundwater per day from two exposure points in the plume based on current conditions and at 5 years in the future. One exposure point was near the centerline of the plume, while the other was on the edge of the plume. This information could be used in a cost-benefit analysis of the reduction of human health risk as a function of remediation.

The data supplied for analysis of Site B included an aerial photograph of the site; maps of buildings, roads, and water bodies; hydraulic head data; and concentration data for three contaminants (TCE, VC, and Tc-99) in groundwater wells at 25 locations during one year of sampling.

C Tech staff chose to demonstrate the visualization, sample optimization, and cost-benefit analysis capabilities of EVS-PRO. Health risk analysis was not performed. For sample optimization the analyst chose to demonstrate EVS-PRO's capabilities using the Tc-99 contamination.

Site D Sample Optimization Problem

The Site D problem was a 3-D groundwater sample optimization problem. The objective of this test problem was to test the software's capabilities to select sample locations that accurately define the extent of contamination and then to use the information to estimate the contaminated volume of groundwater as a function of probability.

The data supplied for the analysis of Site D included maps of buildings, roads, and water bodies; concentration data on four contaminants (PCE, DCE, TCE, and TCA) at different depths and locations in 33 groundwater wells for five consecutive sampling periods; hydraulic head data; and geologic boring data. The C Tech analyst decided to use this information to visualize the original data set and did not perform sample optimization. C Tech's objective

was to demonstrate the power of EVS-PRO in automating data visualization.

Site N Sample Optimization Problem

This test problem was a surface soil contamination problem for three contaminants (As, Cd, and Cr). The test problem was designed to assess the accuracy with which the software can be used to predict sample locations to define the extent of surface soil contamination above certain predetermined threshold concentrations. The threshold concentrations for each contaminant are shown in Table 5. Budgetary restraints limited the number of additional sample locations to 80. Because of the limited number of samples, the analyst was asked to supply estimates of the extent of contamination based on the confidence in the results.

The analyst was given an extensive data set for the three contaminants over a small highly contaminated area of the site (<10 acres). The problem required the analyst to develop a sample optimization scheme to define the extent of contamination for the entire site (125 acres). Site maps with roads, buildings, and water bodies were also provided. The C Tech analyst used arsenic contamination values to make sample optimization decisions for this problem.

Site S Sample Optimization Problem

The Site S sample optimization problem focused on a 3-D groundwater contamination problem for a single contaminant, CTC. The objectives of this problem were to develop a sampling strategy to define the 3-D region of the plume at threshold concentrations of 5 and 500 µg/L and confidence levels of 10, 50, and 90%; to estimate the volume of contaminated groundwater at the defined thresholds; and to calculate human health risks to support cost-benefit decisions. The C Tech analyst performed the problem and estimated the plume location and

Table 5. Site N soil contamination threshold concentrations (mg/kg) for the sample optimization problem

Contaminant	Minimum threshold concentration	Maximum threshold concentration
Arsenic (As)	125	500
Cadmium (Cd)	70	700
Chromium (Cr)	370	3700

volume as a function of three probability levels (25, 50, and 75%).

The data supplied for analysis of this problem included geologic cross-section data, hydraulic head data, hydrologic and transport parameters, and contaminant concentration data from 24 monitoring wells. Data for 19 of these wells had been collected at 5-ft vertical intervals; data for the other 5 wells had been collected on 40-ft vertical intervals. A total of 434 contaminant sample locations and values were provided to the analyst. To focus only on the accuracy of the analysis, the problem was simplified. Information regarding surface structures (e.g., buildings and roads) was not supplied to the analysts. In addition, the data set was developed such that the contaminant concentrations were known exactly at each point (i.e., release and transport parameters were specified and concentrations could be determined from an analytical solution). This analytical solution permitted a reliable benchmark for evaluating the accuracy of the software's predictions.

Site T Cost-Benefit Problem

The Site T problem was a 3-D groundwater contamination cost-benefit problem. The data supplied for analysis of this problem included maps of buildings and roads, soil boring data for 23 wells, and contamination data for four organic contaminants [ethylene dibromide (EDB), dibromochloropropane (DBCP), dichloropropane (DCP), and CTC]. This site was characterized by a complicated subsurface structure. The C Tech analyst decided to demonstrate EVS-PRO's capabilities in representing the subsurface stratigraphy of the site in 3-D rather than perform another cost-benefit analysis.

Evaluation of EVS-PRO

Decision Support

EVS-PRO provides decision support through 3-D visualization of environmental data such as contaminant concentration contours, quantifying uncertainties in interpolation predictions, recommending additional sample locations to reduce uncertainties, and providing statistical information about the extent of contamination. In the demonstration, C Tech used EVS-PRO to import data on contaminant concentrations, hydraulic heads, and geologic structure from ASCII text files and to import visual data such as aerial photographs and maps of buildings, roads, and water bodies from

.jpg, .dxf, and .shp files. EVS-PRO was used to integrate this information on a single platform and place the information in a 3-D visual context. EVS-PRO was used to generate 3-D maps of concentration contours and estimates of the volume of contaminated media as a function of the probability of exceeding threshold concentrations. Maps of uncertainty were generated to highlight the regions of the sites that would require additional sampling to further refine the estimate of location and size of the contaminated area. The accuracy of the analyses is discussed in the section comparing results from EVS-PRO with baseline data and analysis.

Documentation of the EVS-PRO Analysis and Evaluation of the Technical Approach

For each problem, C Tech provided a detailed description of the steps necessary to import the data into EVS-PRO and perform the desired analysis. The steps proceeded logically, and manipulations to arrange the data in the EVS-PRO data structure were relatively simple: Data files were supplied to the analyst in .dbf format. These files were then imported into a program such as Microsoft Excel, reformatted in the structure required by EVS-PRO, and saved in comma-delimited ASCII text file format.

C Tech also provided the parameters for contouring in the output files and problem documentation. The technical approach used by C Tech followed standard practices. However, the analyst often relied on default parameters supplied by EVS-PRO software for performing geostatistical analysis and interpolation. Selection of these parameters on a problem-specific basis would have improved the accuracy of the EVS-PRO analyses. This is discussed in more detail in the evaluation of the Site N sample optimization problem and the Site B and the Site S contaminated volume estimates.

Comparison of EVS-PRO Results with the Baseline Analysis and Data

Site A Cost-Benefit Problem

C Tech used EVS-PRO to analyze the distribution of PCE and TCA contamination at Site A. To illustrate the software's capabilities in generating 3-D visualization of the data, the analyst generated 3-D maps of the regions of contamination above two threshold concentrations at three probability levels. A scale of coordinates and surface features was included on the maps to provide a frame of reference. These files were generated using targa (.tga) formatting in two resolutions. EVS-PRO also

generated four animations depicting the 3-D extent of contamination. The animations rotated the viewing angle of the contamination through 360° to provide a more complete view of the contamination. In addition, EVS-PRO was used to estimate the volume of contamination at the three probability levels and two threshold concentrations.

Figure 1 shows the EVS-PRO representation of the 100- $\mu\text{g/L}$ PCE plume at the 50% probability level (nominal plume). This visualization integrates a number of different pieces of information. The volume predicted to be contaminated above the threshold with 50% probability is represented by the solid region. Dimensions (elevation, easting, and northing) are provided on the figure as a frame of reference. The ground surface is represented as the sloping colored plane at the top of the figure. The elevation of the ground surface was determined from the data supplied as part of the problem. The ground elevation contour key is at the bottom right of the figure. Site features such as the local river and buildings are draped over the ground-surface contour map. The river can be seen as the blue line on the

northern part of the map. Buildings are difficult to see from this perspective; however, a residential community can be seen at the southeast corner as the series of small markings. In the subsurface region of the visualization, lines with a series of circular markers represent well locations and data collection points as a function of elevation. The circles are color-coded to match the measured value at that point. The concentration key, at the top left of the figure, indicates blue as the lowest concentration and red as the highest. The figure also integrates the data on the bedrock elevation at the site and constrains the predicted plume boundary to be above the bedrock at all locations. The monitoring wells were sampled at 5-ft intervals until bedrock was reached. Therefore, an approximate idea of the location of the bedrock can be obtained from the deepest sample location in each well. The red regions in the plume lying just above the bedrock at the southwest corner of the plume indicate high predicted concentrations; it can be inferred from the visualization that the contaminant has migrated downward to the bottom of the aquifer. This emphasizes the value of a 3-D representation of the data.

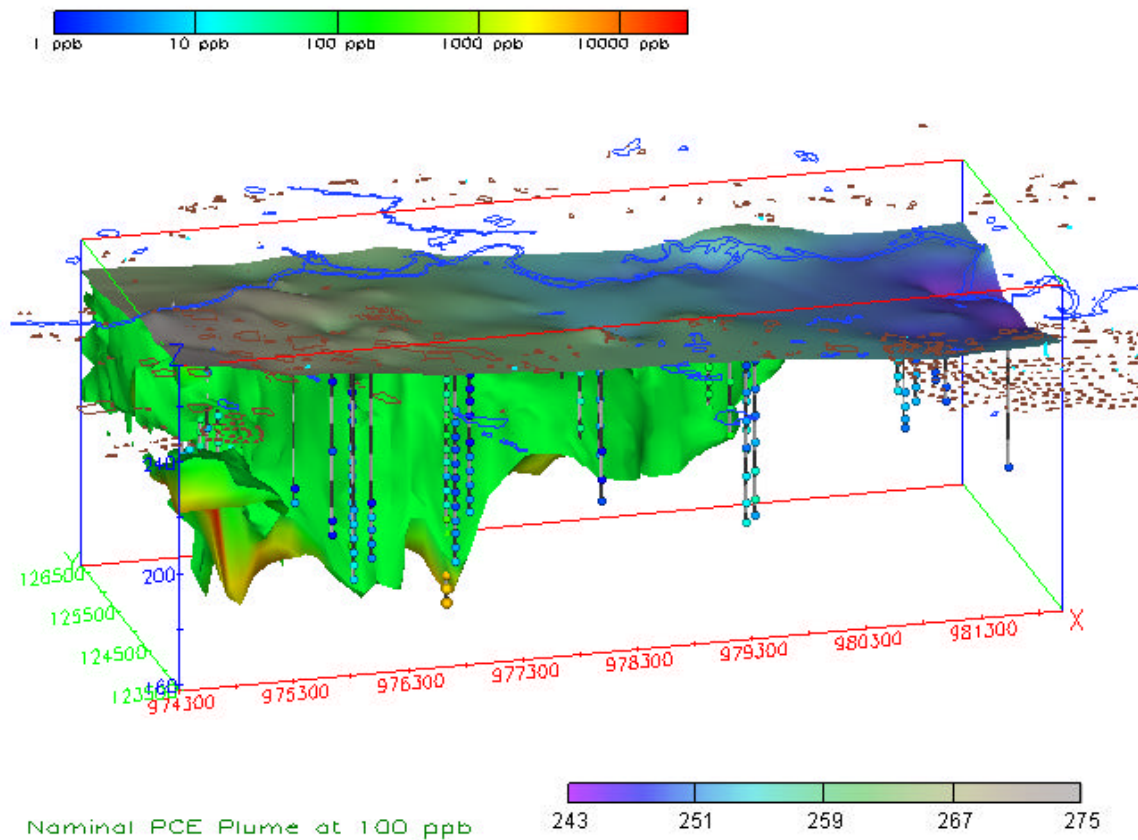


Figure 1. EVS-PRO representation of the Site A 100- $\mu\text{g/L}$ PCE plume at the 50% probability level.

The review of the EVS-PRO visualization output demonstrated that the locations of all features (river, buildings, wells, etc.) were accurately mapped. A comparison of the ground surface elevation (top colored surface in Figure 1) with a similar analysis performed by the evaluation test team using Surfer indicated general agreement between the two approaches. Because of the perspective in Figure 1, it was not possible to evaluate the differences between the two approaches quantitatively. A comparison of the EVS-PRO depiction of concentration (the color-coded circles in Figure 1) with the data showed that the data were accurately represented. The use of this feature permits the analyst to see how well the contour (solid surface) matches the measured data.

The technical team performed a baseline analysis with the same data set using the 2-D interpolation routines in Surfer. The analysis was performed by dividing the subsurface into ten 2-D slices as a function of sample elevation. Most slices were 10 ft thick, but the top slice was only 5 ft thick [260–265 ft above mean sea level (MSL)], and the bottom slice was 15 ft thick (165–180 ft above MSL). If more than one data point was measured in the vertical slice, the maximum value was used to determine the extent of contamination. The baseline analysis was performed for two contaminants, PCE and TCA. Figure 2 represents the nominal PCE plume at 100 $\mu\text{g/L}$ (blue) and 500 $\mu\text{g/L}$ (red) for data collected at elevations between 210 and 220 ft above MSL. The figure provides a top view with the river and the easting and northing scales providing points of reference. Sample locations are marked with a

filled circle. Similar figures were developed for each of the ten layers for both contaminants.

The technical team compared the predicted contamination zones at the threshold concentrations for the two contaminants (100 and 500 $\mu\text{g/L}$ for PCE; 5 and 50 $\mu\text{g/L}$ for TCA). The analyst was supplied with hydraulic head data that indicated groundwater flow was from west to east in a direction that was essentially parallel to the river. There was general agreement between the baseline analysis and the EVS-PRO results in the downstream region of contamination. The differences in approach (2-D vs 3-D analysis and different interpolation parameters) made a quantitative comparison between the baseline and EVS-PRO results impossible. The conclusion of this review is that, in general, EVS-PRO generated acceptable 3-D depictions of the groundwater contamination for this problem at the 50% probability level.

In two areas, however, there were large discrepancies between the baseline and EVS-PRO analyses. The EVS-PRO approach predicted large amounts of contamination at the northwest corner of the site, north of the river, at locations where there were no contamination data (Figure 1). This prediction was caused by the high concentrations of contaminant at nearby wells. However, groundwater flow data indicated that this region was upstream from the source area. The analysis performed by C Tech on Site A did not utilize the groundwater flow data provided. Rather, the analysis was conducted strictly as geostatistical estimation. This resulted in

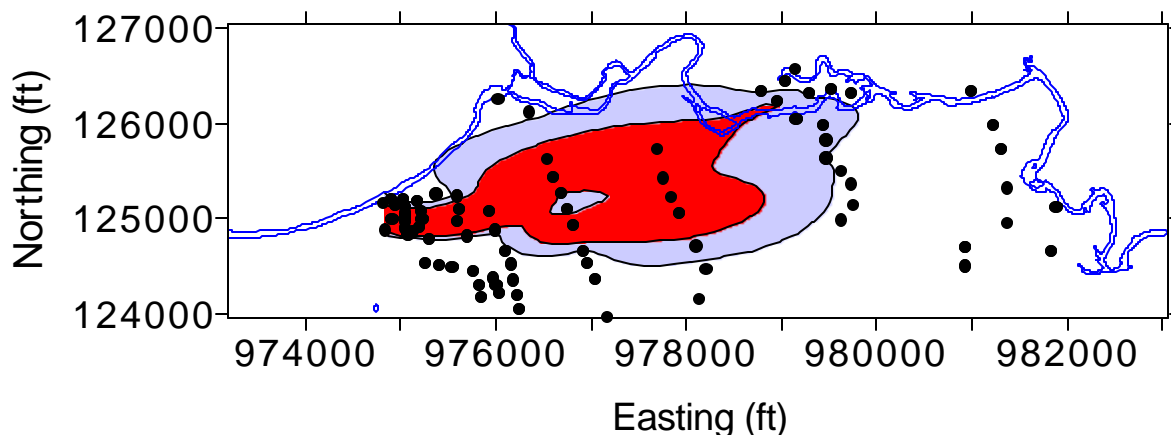


Figure 2. Baseline representation of the Site A nominal PCE plume at 210–220 ft above MSL obtained using Surfer. The red contour represents the 500- $\mu\text{g/L}$ threshold and the blue contour represents the 100- $\mu\text{g/L}$ threshold.

unrealistic estimates upstream of the source area. The C Tech analyst should have bounded the plume upstream and perpendicular to the source to ensure that contamination would not be extrapolated in these directions. In contrast, the baseline approach did not depict this contamination because its interpolation parameters were optimized to minimize this effect and exclude regions upstream from the source area in its analysis. An example of the baseline analysis for PCE contamination at elevations between 210 and 220 ft above MSL is provided in Figure 2. In this figure, blue indicates the 100- $\mu\text{g/L}$ contour and red indicates regions above 500 $\mu\text{g/L}$. In the baseline analysis, contamination is not predicted north of the river.

The other region in which there were major differences between the baseline and EVS-PRO analyses was at deeper subsurface elevations (160–200 ft above MSL). This is the region in which the top of the bedrock is typically found. The baseline analysis did not constrain the predicted zones of contamination to those regions that were above the bedrock and therefore tended to overpredict the spreading of contamination at these depths. This is illustrated in Figure 3, which shows predicted PCE contours at elevations between 180 and 190 ft above MSL. Figure 3 also shows the contour of the bedrock elevation at 190 ft above MSL. Regions within the brown contour line have bedrock depths

lower than 190 ft. As can be seen from the figure, the sample locations marked with the filled circles are all within the elevation contour boundaries, as expected. However, the predicted spread of contamination includes many regions in which the bedrock elevation is higher than 190 ft above MSL. This is clearly incorrect and illustrates the limitations of using the 2-D approach. In practice, the 2-D analysis could have been repeated, limiting the concentration interpolations to only the regions in which bedrock did not exist at that elevation, but this would have required considerable effort. The EVS-PRO model correctly depicts the contamination as a function of depth. In Figure 1, it can be seen that contamination regions at elevations of 180–190 ft above MSL are confined to the regions above the bedrock. For complex systems, the 3-D approach used by EVS-PRO is superior to a 2-D approach.

The C Tech analyst used EVS-PRO to estimate the plume boundary as a function of probability and provided 3-D plume maps of the contaminated region at three probability levels. Figure 4 presents the 10% (maximum), 50% (nominal), and 90% (minimum) probability plume maps for PCE at the 500- $\mu\text{g/L}$ contour. Figure 5 presents the 10, 50, and 90% probability plume maps for TCA at 50 $\mu\text{g/L}$. The depictions are similar to Figure 1 and contain the same types of information (e.g., ground elevation, surface features, well and sample

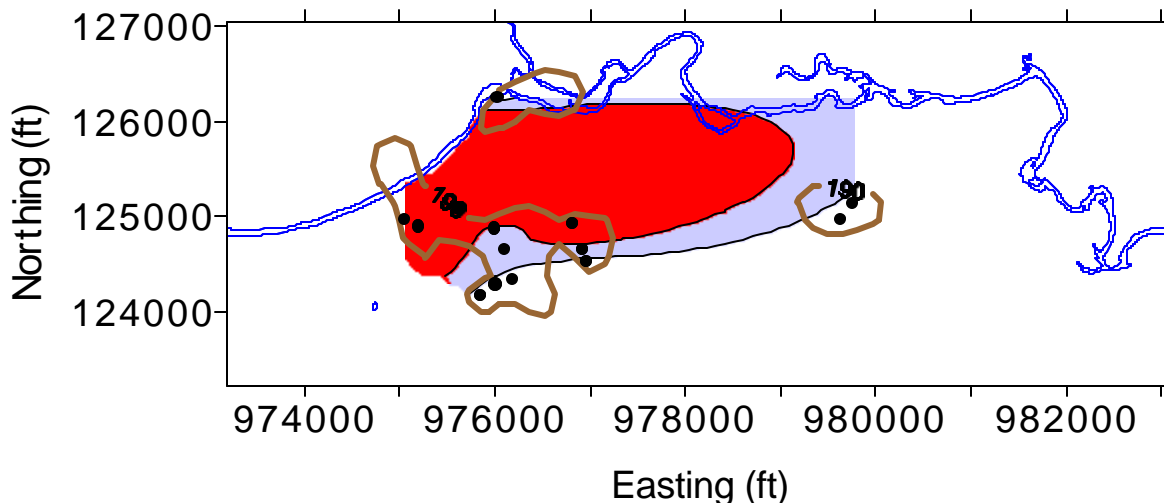


Figure 3. Baseline representation of the Site A nominal PCE plume at 180–190 ft above MSL obtained using Surfer. The red contour is the 500- $\mu\text{g/L}$ threshold, and the blue contour is the 100- $\mu\text{g/L}$ threshold. The brown contour lines represent bedrock elevations. Regions inside the brown contours are the only sections of the site with a confining bedrock layer below 190 ft.

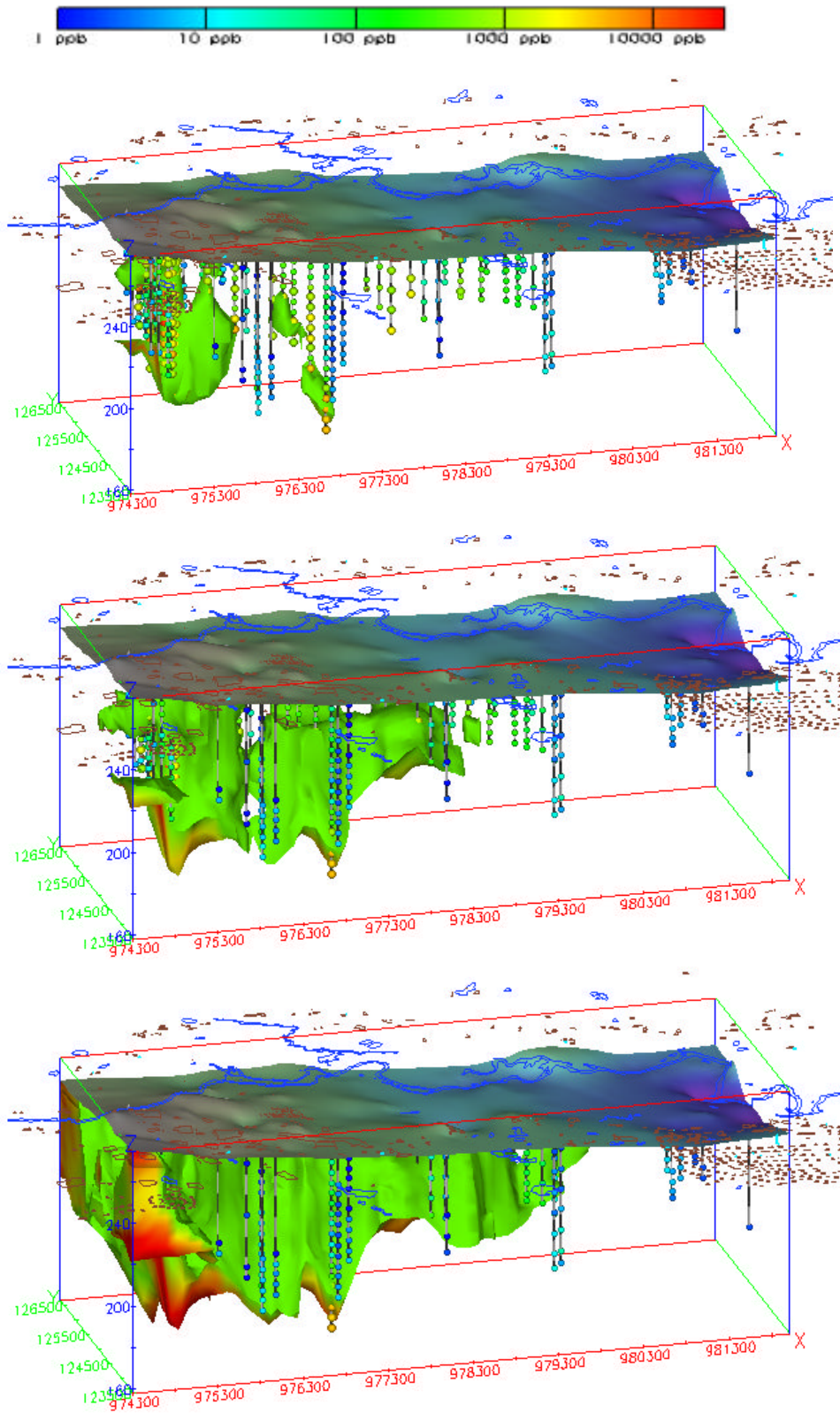


Figure 4. EVS-PRO representations of plumes of PCE at the 500- $\mu\text{g/L}$ threshold concentration at 90% (top), 50% (middle), and 10% (bottom) probability levels.

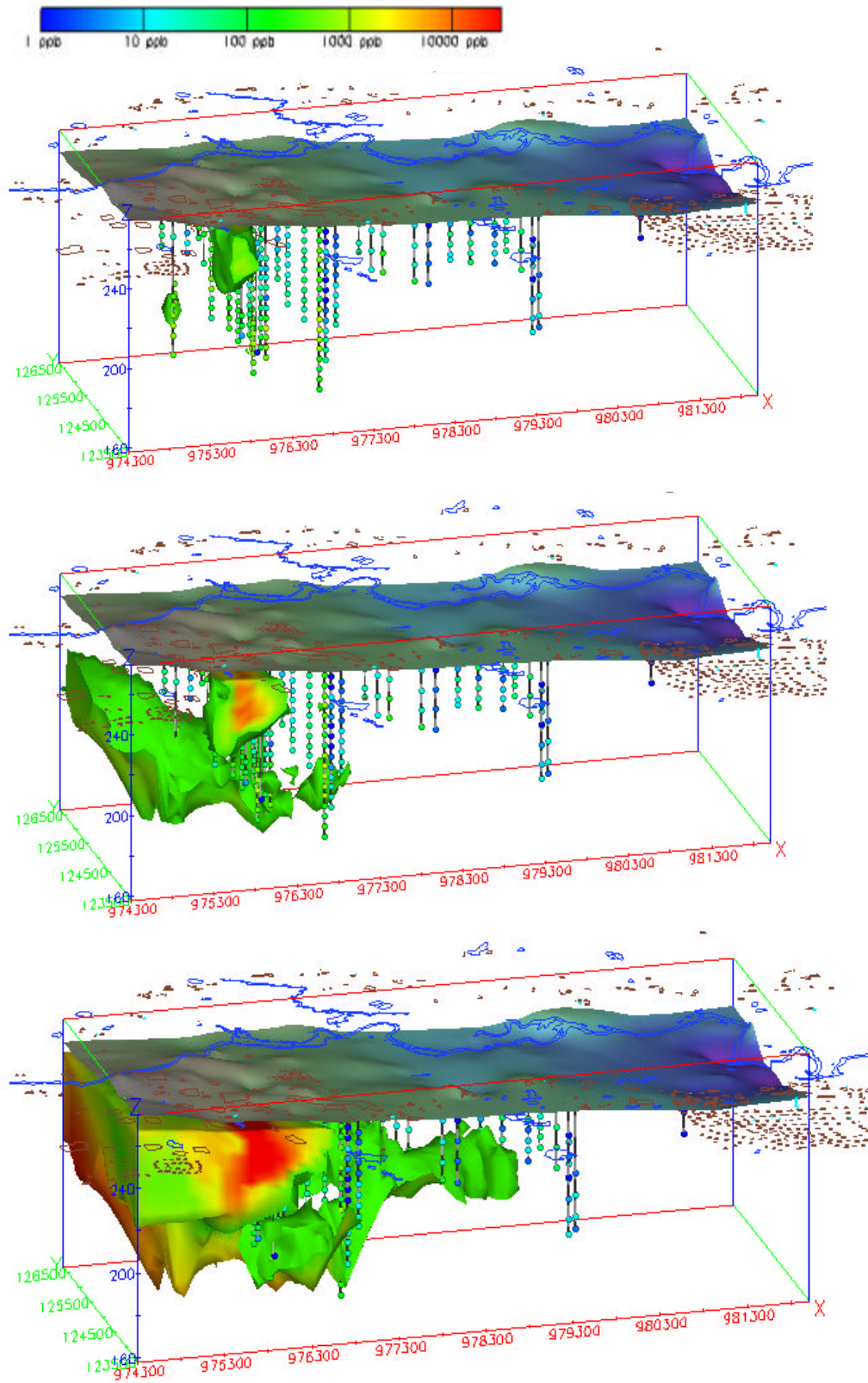


Figure 5. EVS-PRO representations of plumes of TCA at the 50 $\mu\text{g/L}$ threshold concentration at 90% (top), 50% (middle) and 10% (bottom) probability levels.

locations with color-coded representations of measured concentration data, and contour regions).

Figure 4 shows that the 90% 500- $\mu\text{g/L}$ plume of PCE contamination (minimum volume, 90% certainty that the plume exists) is located primarily at the northwest corner of the map and has not spread far. The 50% 500- $\mu\text{g/L}$ PCE plume is considerably larger than the 90% plume, and there is an indication of a hot spot directly below the source just above the confining bedrock layer (since the red area on the map indicates a concentration $>10,000 \mu\text{g/L}$). The 10% 500- $\mu\text{g/L}$ plume is shown to have spread throughout the site, including areas north of the river in regions for which measured data do not exist. Several hot spots can be seen just above the confining bedrock layer. The difference in plume estimates at the three different probability levels reflects the choice of contouring parameters and amount of knowledge about the contamination.

Figure 5 shows the main region of the 90% probability 50- $\mu\text{g/L}$ TCA plume at the southwest corner of the map, in a different location than the PCE plume. However, there is an indication of TCA contamination in the northwest corner of the site in a location similar to the hot spot of the PCE plume. The 50% 50- $\mu\text{g/L}$ TCA plume shows large amounts of contamination (the red zone on the map) at the southwest corner of the site. The lower probability (i.e., less confidence in estimated TCA concentrations) has the effect of spreading the predicted zone of contamination downstream and to the northwest corner of the site, which does not have measured data. In fact, most of the volume of predicted contamination occurs in regions without measured data. The 10% 50- $\mu\text{g/L}$ TCA plume indicates that the complete western section of the site may be contaminated above the threshold concentration. Much of this region is upstream from the source. These predictions are the result of the high measured values near the boundary of the modeled region. More information—e.g., additional data on contamination, groundwater flow, or source locations—is required to bound the plume in this region.

In addition to the single-perspective visualizations of the plume shown in Figures 1, 4, and 5, EVS-PRO also generated animations for the 50% plumes for both contaminants at both threshold concentrations in .avi format. These files rotate the perspective 360°

around the outside edge of the site and permit the analyst to gain a much better understanding on the location of contamination. [Click here](#) for an example of this type of visualization for the nominal PCE plume at 500 $\mu\text{g/L}$.

The C Tech analyst also provided estimates of the contaminated volume as a function of threshold concentration and probability level (Table 6). To establish a basis for comparison, the baseline analysis was performed by calculating the contaminated volume in each of the ten vertical 2-D slices and summing them to obtain the total volume. The baseline volume estimates were constrained by the elevation of the bedrock (i.e., if bedrock was present, it was assumed to be uncontaminated). As Table 6 shows, there is relatively good agreement between the EVS-PRO and baseline nominal estimates of the PCE plume volume, with the EVS-PRO estimates being 22% lower at the 100- $\mu\text{g/L}$ threshold and 37% lower at 500 $\mu\text{g/L}$. Comparison of the nominal estimates of the TCA plume volume shows that the EVS-PRO estimates are considerably greater than the baseline estimates, with the EVS-PRO estimate being almost twice as large as the baseline estimate at 5 $\mu\text{g/L}$ and almost eight times larger at 50 $\mu\text{g/L}$. The cause for this large discrepancy is the EVS-PRO prediction of the plume to the west and north of the site in regions where measured data are not available. Figure 5 shows that most of the predicted volume of the nominal plume occurs in this region. The 90% probability plume shown in Figure 5 (top) is similar to the baseline analysis nominal plume at the 50% probability level, and the predicted volumes are also similar. The differences in approaches (2-D vs 3-D) and the use of nonoptimal interpolation parameters in EVS-PRO led the technical team to conclude that performing a complete geostatistical analysis would not aid in understanding the performance of EVS-PRO at this site. However, the EVS-PRO geostatistical approaches and analyses performed for Sites B and S are evaluated in other sections of this report.

Site B Sample Optimization and Cost-Benefit Problem

The C Tech analyst chose to demonstrate the visualization, sample optimization, and cost-benefit analysis capabilities of EVS-PRO on the Site B problem. For sample optimization, the analyst chose to demonstrate EVS-PRO's capabilities using the Tc-99 contamination data. Starting with the initial

Table 6. EVS-PRO and baseline estimates of the volume of PCE and TCA contamination (ft³) at Site A as a function of probability

Analysis	90% probability (minimum)	50% probability (nominal)	10% probability (maximum)
<i>PCE at 100 mg/L</i>			
EVS-PRO	7.97E7	2.55E8	5.39E8
Baseline	—	3.28E8	—
<i>PCE at 500 mg/L</i>			
EVS-PRO	1.06E7	8.05E7	3.00E8
Baseline	—	1.28E8	—
<i>TCA at 5 mg/L</i>			
EVS-PRO	2.36E8	5.98E8	1.03E9
Baseline	—	3.13E8	—
<i>TCA at 50 mg/L</i>			
EVS-PRO	9.49E6	7.89E7	2.95E8
Baseline	—	1.06E7	—

25 samples, the analyst selected several additional sample locations and requested data at these locations to further define the extent of Tc-99 contamination. The information was provided, and the process was repeated until a total of 23 additional locations had been selected. The technical team concluded that the number of samples for defining the plume using geostatistics was slightly larger than anticipated. Although the EVS-PRO software selects default parameters for modeling spatial correlation, optimization of these parameters would have resulted in approximately 15–20 additional sample locations to define the Tc-99 plume at the specified thresholds of 10,000 and 40,000 pCi/L. EVS took 5–8 more samples than would have been required had the analysis routines been optimized. Requiring these additional sample locations would lead to additional project costs. Incorporation of information about groundwater flow into the sample optimization process would also help reduce the number of additional samples.

Using the final data set of 48 sample locations, EVS-PRO generated maps of the Tc-99 plume at the two threshold concentrations at three probability levels: 25% (maximum), 50% (nominal), and 75% (minimum). Color-coded circles represented the Tc-99 concentrations. The maps provided an outline of the region containing Tc-99 above the threshold concentration at a fixed probability level. Surface features and a scale of coordinates were included on the maps to provide a frame of reference. An aerial

photograph was also geo-referenced on some maps. A total of six maps were provided for Tc-99.

A similar analysis was performed for the other two contaminants, TCE and VC, using the original data set (sample optimization was not performed). C Tech provided an animated file containing the hydraulic head data representing the depth of the top of the water table and an aerial photograph of the site. C Tech also provided files generated by EVS-PRO using virtual reality modeling language (VRML) which could be viewed and navigated with the free downloadable software plug-ins. (C Tech recommends the Cosmo Viewer that can be obtained from www.karmanaut.com/cosmo/player/.) Navigation permits the viewer to rotate the drawing to any angle to examine the extent of contamination. The data were also used to generate a cost-benefit analysis of the volume contaminated vs cleanup threshold for all three contaminants.

Figure 6 is the EVS-PRO representation of the hydraulic head data with the aerial photograph and the site map draped on the ground surface. Review of this figure demonstrated that the aerial photograph, which was in a .jpg file format that was correctly mapped to the site. This can be seen in the match between the photograph and site features such as buildings and rivers supplied on drawing exchange files (.dxf). Comparison of the hydraulic head contour map with the data and a separate contour map developed using Surfer showed that the

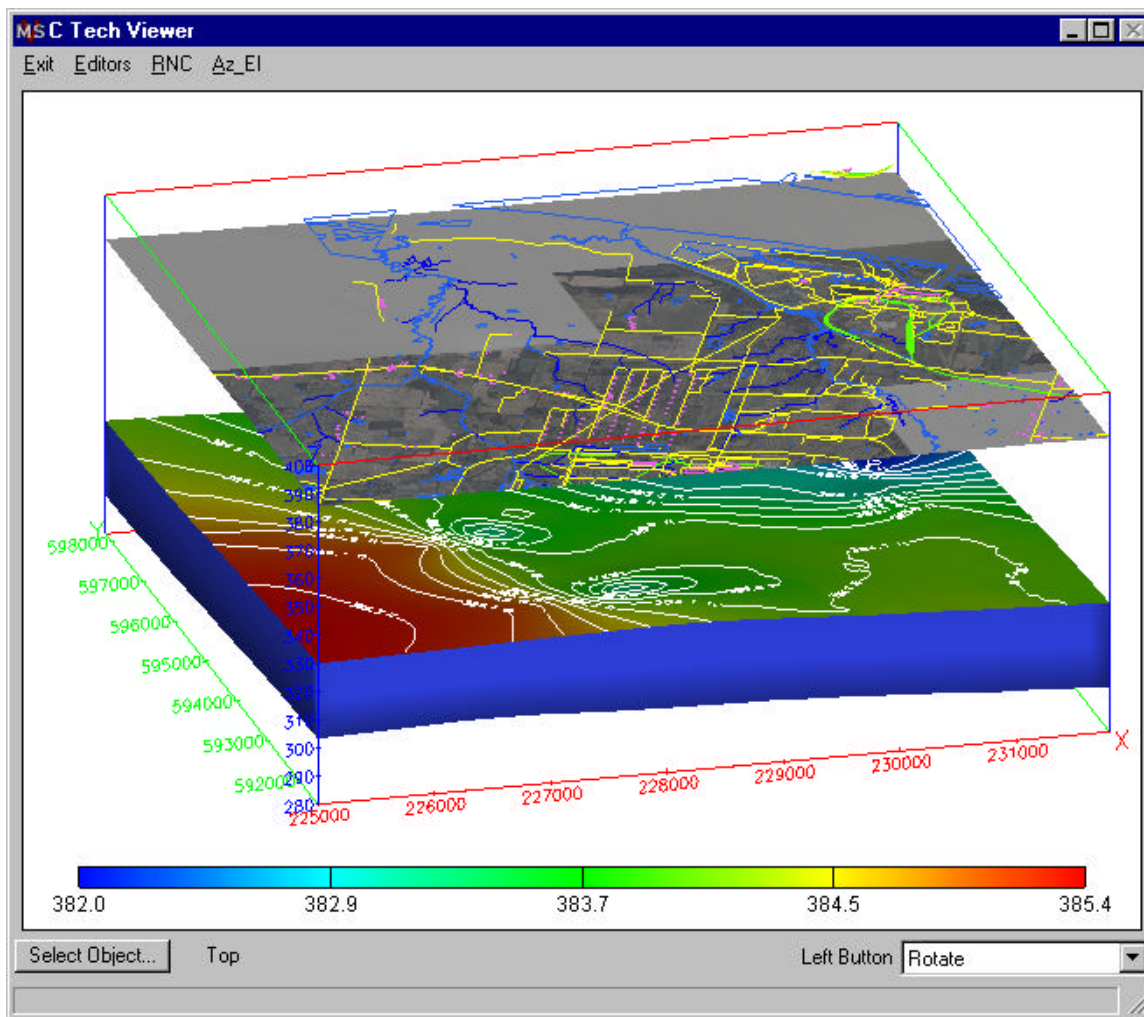


Figure 6. EVS-PRO representation of Site B water levels. Water levels are represented through contours and changes in elevation at the lower surface by the color key at the bottom of the figure. The top surface contains an aerial photograph overlaid with a map of site features (buildings, roads, and water bodies).

EVS-PRO map accurately represented the data. [Click here](#) to view an animation generated by EVS-PRO.

Figure 7 is the EVS-PRO representation of the 10,000-pCi/L Tc-99 plume at the 50% probability level (nominal plume) after sample optimization had been completed. This problem is effectively a 2-D problem because the aquifer had a uniform thickness of approximately 25 ft throughout the problem domain and data were therefore not collected as a function of depth in the aquifer. The region predicted to be contaminated above 10,000 pCi/L with 50% probability is represented by the solid surface, with the height of the surface representing the thickness of the aquifer. The solid surface is color-coded to represent contaminant concentrations,

with yellow representing the threshold value and red representing the highest concentrations (>100,000 pCi/L). Dimensions (elevation, easting, and northing) are provided on the figure as a frame of reference. The ground surface is represented by use of the aerial photograph, and surface features obtained from drawing files are highlighted. In the subsurface region of the visualization, lines with a series of circular markers represent well locations and data collection points. The circles are color-coded, using the concentration key, to match the measured value at a given point.

The EVS-PRO visualization of plume location as a function of threshold concentration (Table 4) and probability level was reviewed for each contaminant (Tc-99, TCE, and VC). The review confirmed that

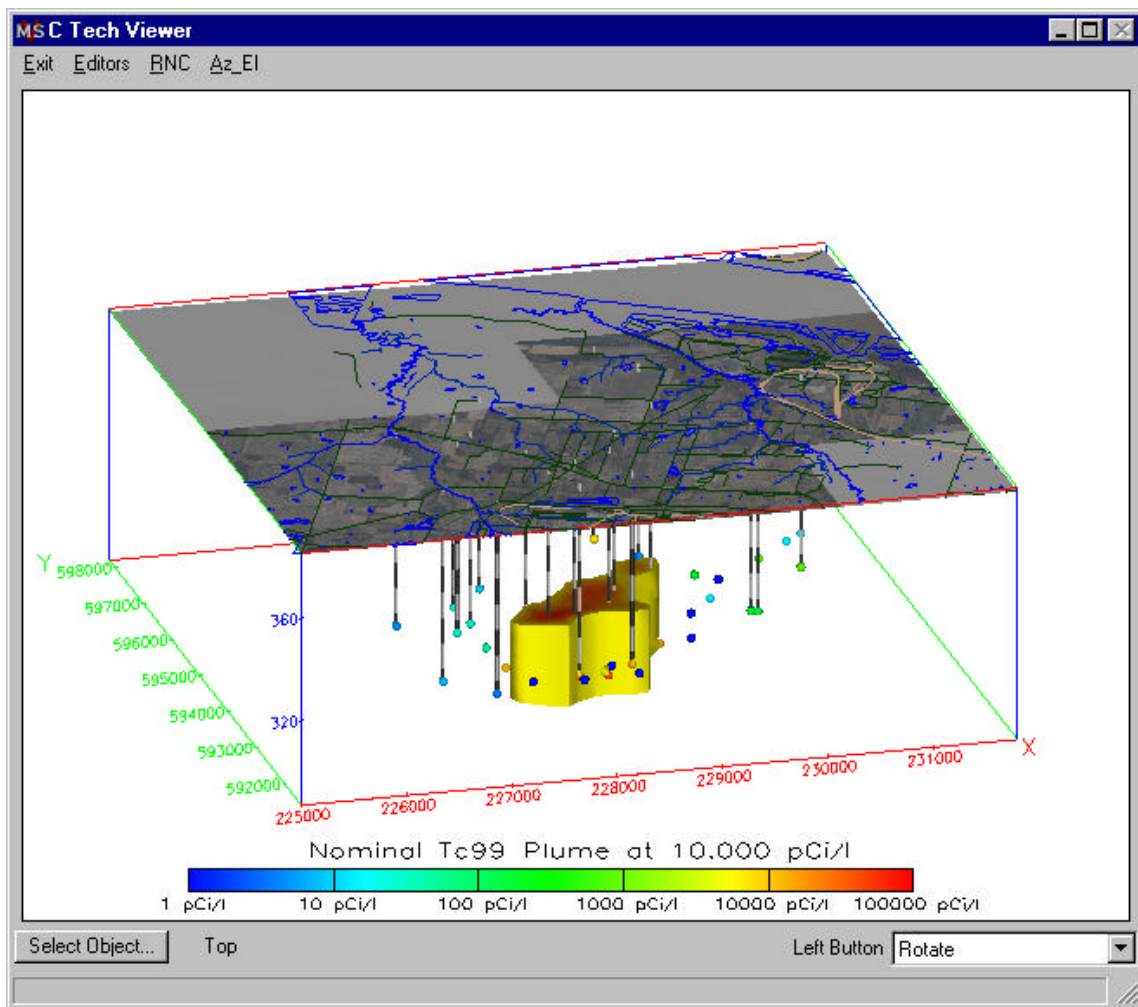


Figure 7. EVS-PRO representation of the Site B 50% probability level Tc-99 plume above the 10,000pCi/L threshold after completion of sample optimization. The top surface contains an aerial photograph of the site and maps of surface features. Color-coded circles represent data measurements.

all features (river, buildings, wells, etc.) were accurately mapped. Comparison of the depiction of concentration (color-coded circles in Figure 7) with the data showed that the data were accurately represented. The use of this feature permits the analyst to see how well the contour matches the measured data.

The technical team performed a baseline analysis with Surfer using the same data set to obtain one estimate of the plume location and volume. In addition to Surfer, two other software packages—GSLIB and Geo-EAS—were used to provide independent analyses of the data and alternative representations for comparison with the Surfer results. These baseline analyses utilized three interpolation routines (IDW, ordinary kriging, and indicator kriging) with varying parameters to

produce the “best fit” of estimated concentrations to the baseline data. Figure 8 presents the baseline analysis obtained using GSLIB and indicator kriging, which is comparable to the EVS-PRO nominal plume for Tc-99. Comparisons of the nominal plume locations were performed for Tc-99, TCE, and VC using the same data set that was used by the C Tech analyst. There was general agreement between the two approaches in the downstream region of contamination. In general, EVS-PRO generated accurate depictions of the groundwater contamination for the nominal estimates (50% probability level) of the Tc-99, TCE, and VC plumes.

The EVS-PRO plume maps at the 25% probability level for both Tc-99 and TCE indicated the potential for contamination in regions at the edge of the

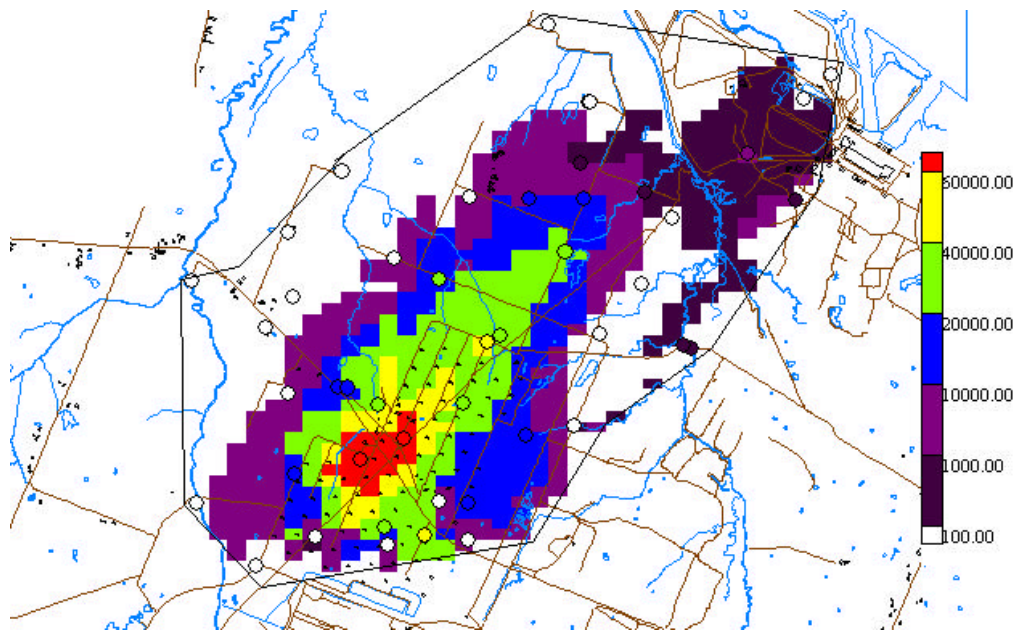


Figure 8. Baseline representation of the Site B Tc-99 plume (concentrations in pCi/L) obtained using GSLIB and the same data set as that obtained by C Tech after sample optimization. Site features such as buildings and waterways are also shown on the map.

modeled domain that did not contain data. This prediction is a reflection of the modeling parameters used for estimating concentrations as a function of probability and the lack of data near these regions. In these regions, EVS-PRO's default contouring parameters predict a large influence from high measured values of concentration in the central region of the plume even though low values are measured closer to the model boundary around the edge of the plume. For example, Figure 9 shows the 25% probability plume (75% maximum plume in EVS-PRO terminology) for Tc-99 at the 40,000-pCi/L threshold level. The map depicts the region containing high measured values of Tc-99 (easting measurements between 227,000 and 229,000, northing measurements between 593,000 and 594,000). The sample optimization procedure has apparently bounded the plume on all sides. (Sample locations are marked on the map and color-coded to indicate concentration.) However, the EVS-PRO prediction as shown in Figure 9 indicates that contamination may be present (with a 25% probability) to the north/northwest and to the southeast of the measured plume. While the prediction is consistent with the statistical structure of the data and the parameters used for interpolation, this does not make physical sense. The region to the north/northwest of the site is not in the direction of groundwater flow; therefore, one would not expect

contamination unless another source of contamination is present. If another source is present, use of the statistical properties of the existing plume does not make sense. The area to the southeast of the plume is downstream from the source region. However, there are several wells with measured data below the 40,000-pCi/L threshold value between the region above the threshold and the region without data predicted to be above the threshold. This distribution of contaminants would require an intermittent source. The baseline approach did not depict contamination to the north of the plume because interpolation parameters were optimized to minimize spreading of the plume in directions perpendicular to the groundwater flow (Figure 10). The C Tech analysis performed on Site B did not utilize the groundwater flow data provided. Rather, the analysis was conducted strictly as geostatistical estimation. This resulted in unrealistic estimates upstream of the source area. The C Tech analyst should have bounded the plume upstream and perpendicular to the source to ensure that contamination would not be erroneously extrapolated in these directions. The evaluation team concluded that the EVS-PRO analysis could have been improved if the operator had overridden the default values for geostatistical analysis supplied by EVS-PRO and optimized the geostatistical parameters.

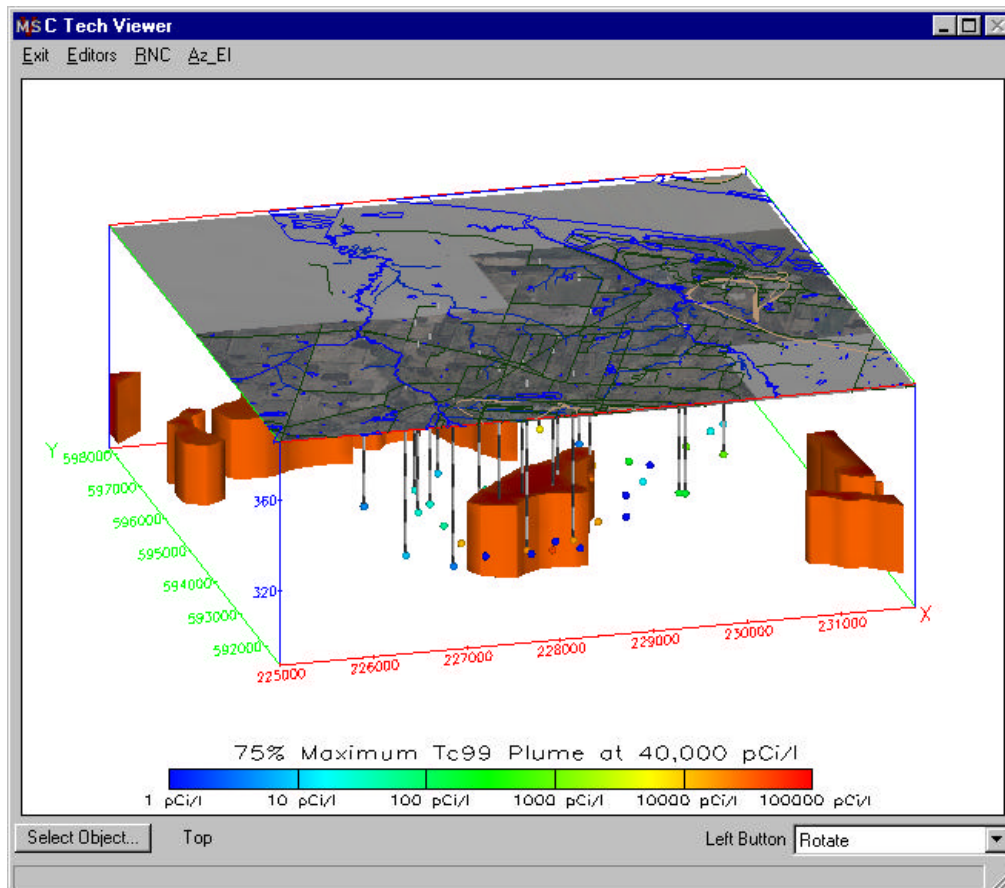


Figure 9. EVS-PRO representation of the Site B 25% probability level (maximum plume volume) Tc-99 plume above the 40,000 pCi/L threshold after completion of sample optimization. The top surface contains an aerial photograph of the site overlaid with maps of surface features. Color-coded circles represent data measurements.

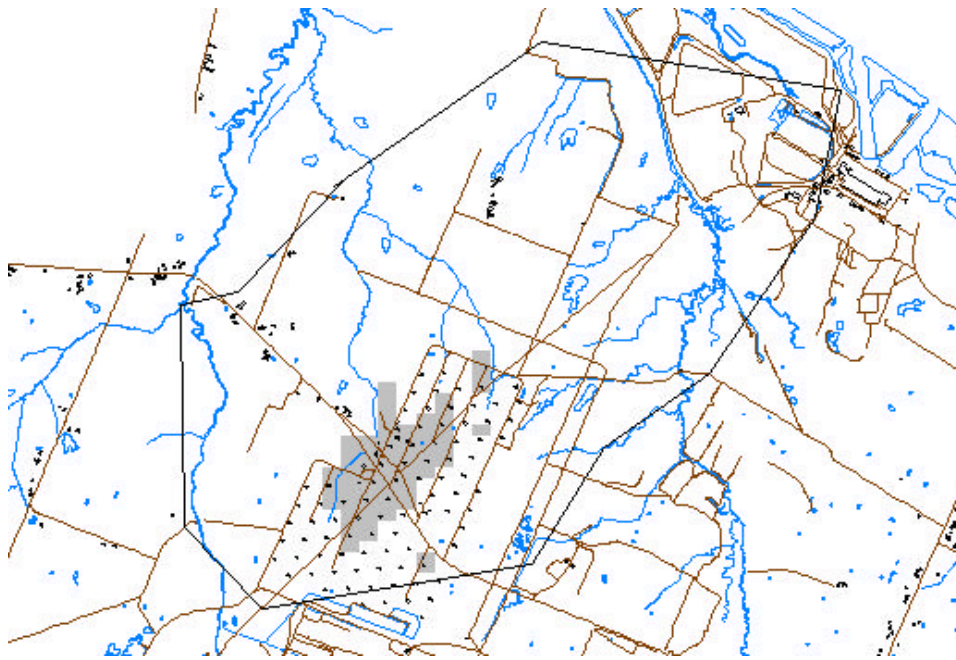


Figure 10. Baseline representation of the Site B 25% probability level Tc-99 plume at 40,000 pCi/L (gray areas). The analysis was obtained using GSLIB and the same data set as that obtained by C Tech after sample optimization. Site features such as buildings and waterways are also shown on the map.

Viewing the information from several different perspectives can enhance understanding of the plume location. EVS-PRO generated several VRML files (.wrl extension) that permitted the reviewers to navigate around the TCE plume as well as an animation that automatically rotated the plume. [Click here](#) to view an example of a 50- $\mu\text{g/L}$ TCE nominal plume generated by EVS-PRO. Figure 11 shows the image that can be rotated in the VRML viewer. In the figure, all wells are labeled and measured values are posted next to the wells. The solid region represents the contaminated volume; coordinates provide a frame of reference. The isolated solid region in the southeast corner is a modeling artifact due to the choice of interpolation parameters. There are no data in this region and it is unlikely that the predicted contamination is real.

The C Tech analyst also provided estimates of the contaminated volume as a function of threshold concentration and probability level for Tc-99 and TCE; these are shown in Table 7 along with baseline estimates. Comparison of the nominal (50% probability) Tc-99 plume volume estimates indicates that there is fairly consistent agreement between the EVS-PRO and baseline estimates at the 10,000-pCi/L threshold, with the EVS-PRO

estimates being 47% lower. At the 40,000-pCi/L threshold, the EVS-PRO volume estimate for the nominal plume is approximately 32% lower than the baseline estimate.

The C Tech analyst used the default contouring parameters selected by EVS-PRO. These parameters are not optimized to obtain volume estimates and tend to overestimate the contamination at low probabilities and underestimate the contamination at high probabilities. This leads to a wide variation in the predicted volume of the plume as a function of probability. In most cases, the EVS-PRO low-probability estimates of the plume (maximum volume) exceed the estimates of the baseline analysis. Conversely, the EVS-PRO high-probability estimates of the plume (minimum volume) are less than the baseline estimates. For example, the plume volume predicted by EVS-PRO for Tc-99 at the 25% probability level at the 40,000 pCi/L threshold is an order of magnitude greater than the volume predicted by the baseline estimate. An examination of Figure 9, which depicts the EVS-PRO prediction for contaminated volume at 25% probability, clearly indicates that most of the predicted volume occurs at the edges of the domain where data are not available.

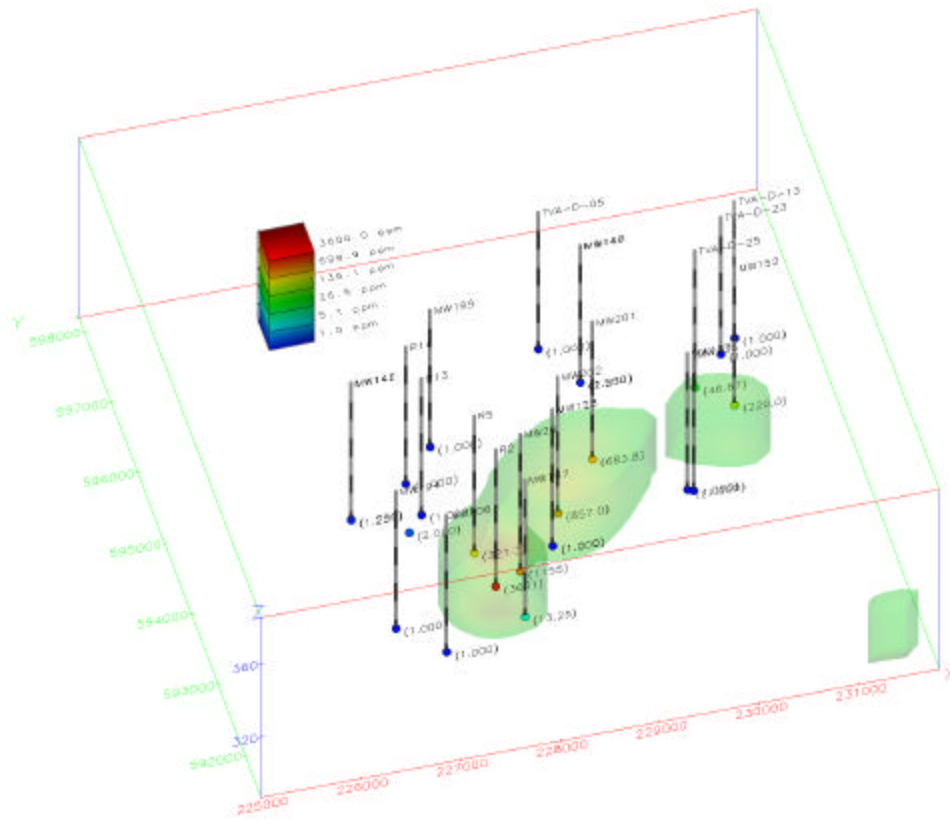


Figure 11. EVS-PRO-generated visualization of the Site B 50% probability TCE plume above the 50-µg/L threshold. Measured concentrations are posted to the map. This is one representation from the .wrl file, which can be rotated to obtain different viewing perspectives.

Table 7. EVS-PRO and baseline estimates of the volume of Tc-99 and TCE contamination at Site B (ft³) as a function of probability

Analysis	75% probability (min-plume)	50% probability (nominal)	25% probability (max-plume)
<i>Tc-99 at 10,000 pCi/L</i>			
EVS-PRO	1.3E7	4.5E7	4.2E8
Baseline	6.9E7	8.5E7	1.1E8
<i>Tc-99 at 40,000 pCi/L</i>			
EVS-PRO	5.3E4	9.4E6	1.3E8
Baseline	1.1E7	1.4E7	1.5E7
<i>TCE at 50 µg/L</i>			
EVS-PRO	4.0E7	8.9E7	4.03E8
Baseline	7.8E7	1.2E8	2.07E8
<i>TCE at 500 µg/L</i>			
EVS-PRO	2.8E6	1.2E7	4.9E7
Baseline	6.4E6	3.1E7	8.6E7

A comparison of the nominal TCE plume volume estimates (Table 7) shows that the EVS-PRO estimates are less than the baseline estimates. The EVS-PRO estimate is 25% lower than the baseline analysis at 50 µg/L, which is a consistent match, and 61% lower at 500 µg/L, a poor match. Comments similar to those for the Tc-99 plume apply to the low and high probability volume estimates for TCE.

Site D Sample Optimization Problem

The data for Site D included information on four contaminants at five different sampling periods in 33 wells. C Tech did not perform sample optimization for the Site D problem. Because the sample optimization capabilities of EVS-PRO had already been demonstrated with three other problems (those for Sites B, N, and S), C Tech chose, instead, to demonstrate the power of its scripting language in rapidly generating visualizations of existing data. EVS-PRO used its scripting language to write a procedure to query the data file to select a single contaminant and all measurements in a single sampling period. This information was used to visualize the original contaminant data and to

produce 2-D and 3-D maps of contamination. The software automatically repeated this process for each of the four contaminants at each of the five sampling periods.

The 2-D maps generated provide a top view of the areal extent of contamination with a site map containing buildings and roads. The 3-D maps show the contamination as a function of depth, with solid and exploded views. The exploded views help in understanding the extent of contamination in different geologic layers. Figures 12, 13, and 14 show the TCE contamination in the third quarter of 1991 in the three views provided. EVS-PRO produced 120 visualizations, showing four contaminants, five sampling periods, three views, and two resolutions of each view; it also provided estimates of the contaminated volume of water above the specific threshold concentration for each contaminant. The entire process was done automatically without operator intervention by use of the script file. The ability to automate data processing and to quickly generate multiple views of the data based on sorting criteria (e.g., contaminant,

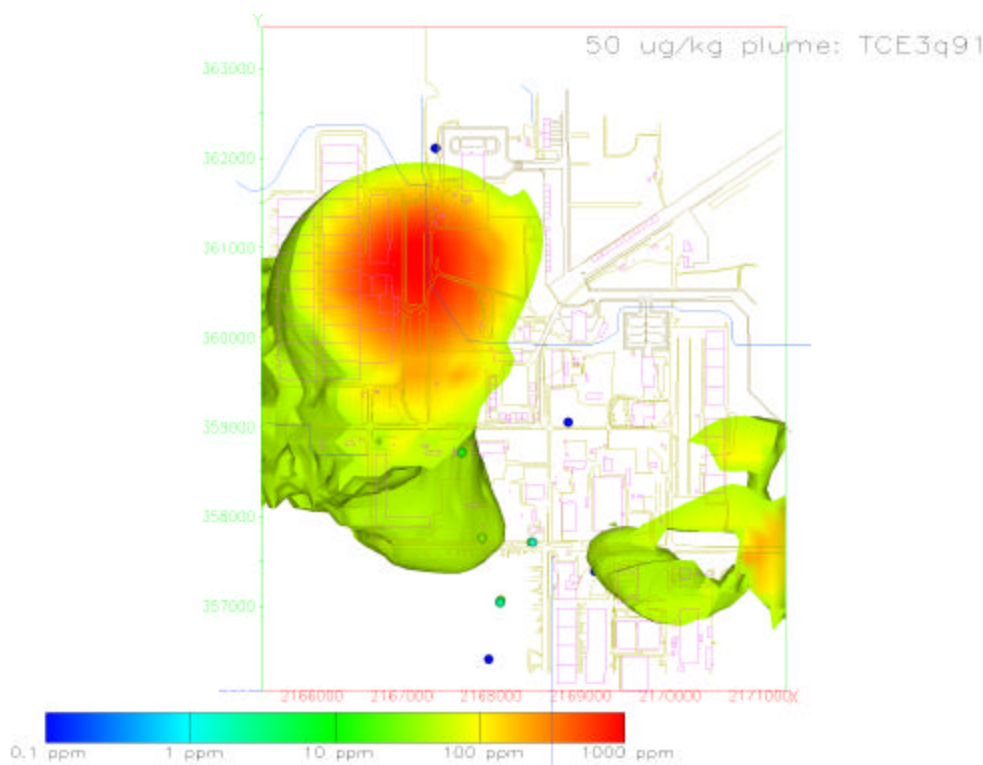


Figure 12. EVS-PRO representation of the Site D nominal TCE contamination above the 50-µg/L threshold, based on third quarter 1991 sampling data. Site feature such as roads and buildings are evident on the map. The scale on the map should be in ppb instead of ppm.

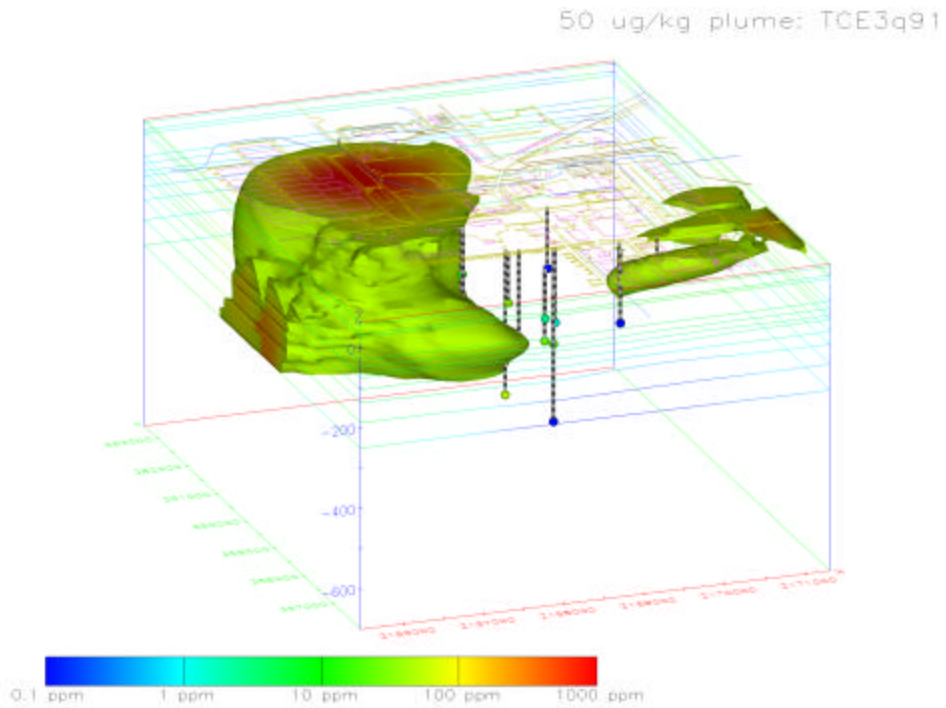


Figure 13. EVS-PRO 3-D representation of the Site D nominal TCE contamination above the 50-µg/L threshold, based on third quarter 1991 sampling data. Site feature such as roads and buildings are evident on the map. The scale on the map should be in ppb instead of ppm.

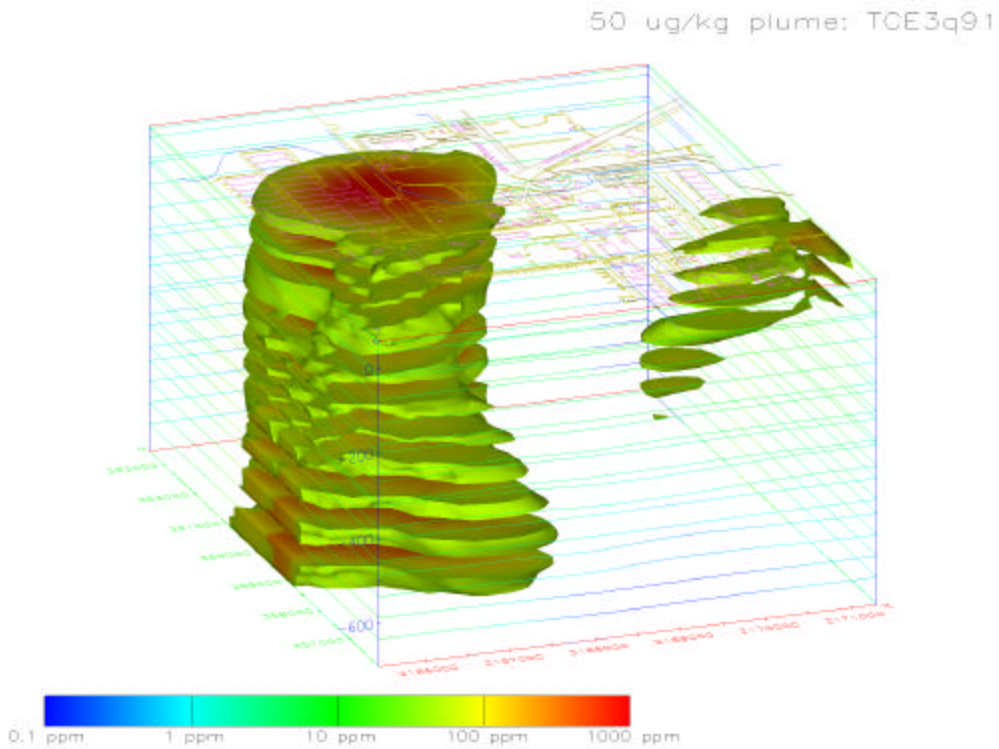


Figure 14. EVS-PRO 3-D exploded view representation of the Site D nominal TCE contamination above the 50-µg/L threshold, based on third quarter 1991 sampling data. Site feature such as roads and buildings are evident on the map. The scale on the map should be in ppb instead of ppm.

time, etc.) is a powerful tool for understanding the existing data. After the script file was completed, the generation of the 120 different views of the data required about ten minutes of computer time.

The technical team reviewed all the visualizations for consistency with the data. The review confirmed that all features (buildings, roads, wells, etc.) were accurately mapped. However, the legends in Figures 11 - 14 were incorrectly labeled. Data were provided in units of parts per billion; however, they are presented in the visualizations in units of parts per million. This labeling error was attributed to the analyst incorrectly setting the units in the software. With the exception this labeling error, the data were accurately depicted on the maps.

The original data at the different sampling periods were often spatially unbounded (i.e., high measured values were obtained without surrounding low measured values). The intent of the problem was for the analyst to use sample optimization techniques to define sample locations to bound the plume and thereby define the nature and extent of the contamination. Since this was not done, the technical review team did not perform a quantitative evaluation of the EVS-PRO results. The technical team concluded that the plumes were not defined with enough accuracy to obtain meaningful estimates for comparison.

Site N Sample Optimization Problem

For the Site N problem, initial contamination data were provided for a small region of the site, and the analyst was asked to define the concentrations of the contaminant for the entire site using only 80 additional samples. Figure 15 presents the site map generated by the technical team; the initial sample locations are marked with the symbol + and arsenic concentration contours at the two threshold concentrations are also displayed. The map also indicates the locations of roads, ponds, and creeks. The C Tech analyst used EVS-PRO to select sample locations to define the extent of contamination for the entire site. Of the three contaminants present at the site, the analyst selected arsenic, which had the highest measured concentrations, as the reference contaminant for sample optimization decisions. This is an acceptable approach because in practice, it is unlikely that a different sample optimization scheme would be developed for each contaminant. The analyst used the geostatistics routines in EVS-PRO to automatically select sample locations to bound the

area of contamination in the small region encompassing the original data. This new information was used to generate the next set of sample locations, and the process continued until the maximum number of allowed sample locations (80) had been specified. With the final data set, EVS-PRO generated arsenic concentration contour maps based on contaminant threshold concentrations and the degree of confidence in the interpolation results. Maps of uncertainty as a function of the number of samples were also provided to illustrate the reduction in uncertainty achieved with increased sampling.

Figure 16 shows the final EVS-PRO arsenic contamination map based on the data after sample optimization was completed. This map represents the 50% probability contamination zone and contains site features (roads and waterways) along with the contours. According to the contour key, red represents the highest concentrations and dark blue the lowest. Unfortunately, the key was determined from EVS-generated values because the changes in color did not match the threshold values (125 and 500 mg/kg) of the problem. This makes interpretation difficult. The contamination depicted apparently represents contamination levels above 500 mg/kg. Color-coded circles mark the sample locations. Examination of the sample locations shows that the contamination was bounded in the southwest corner of the site; however, there are large areas that do not have any samples. This indicates the sample optimization procedure did not cover the entire site.

While performing the Site N sample optimization, the C Tech analyst incorrectly assumed that the contamination across the entire site was correlated to the plume in the initial small-region data set. This caused the software to identify new locations for sampling that were adjacent to the known contamination and resulted in poor coverage in the unexplored region. A more appropriate approach to this problem would be to sample the unmeasured areas using an equal-area approach and distribute a portion of the 80 samples throughout the site. Based on the additional information, geostatistical analysis could be used to further define the contamination zones.

To place the EVS-PRO results on the contamination scale requested in the test problem, the technical

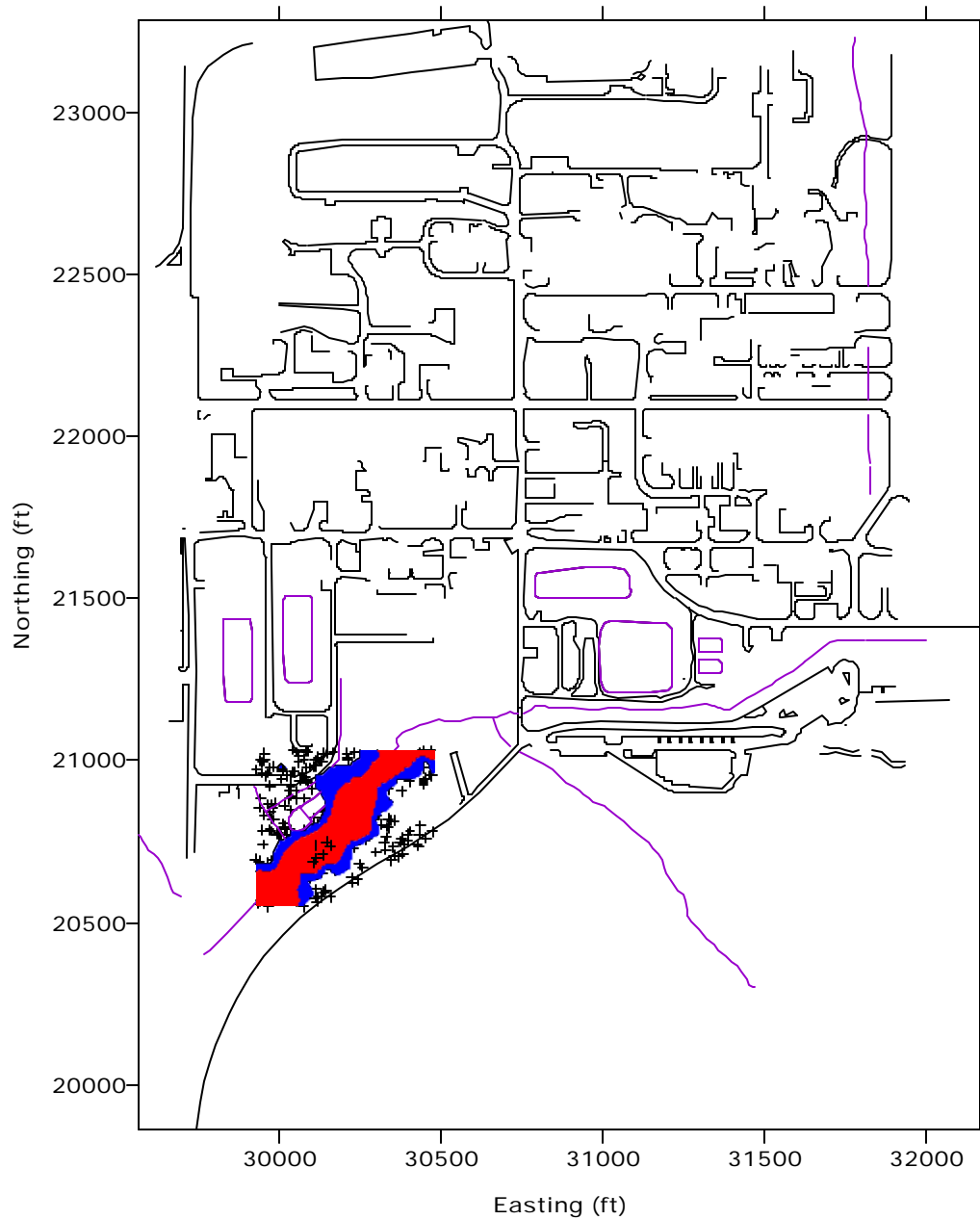


Figure 15. Baseline representation of the Site N arsenic contours at the 125- (blue) and 500- (red) mg/kg thresholds obtained using Surfer and the data provided to the analyst for conducting the sample optimization analysis. Site features such as roads and waterways are provided on the map.

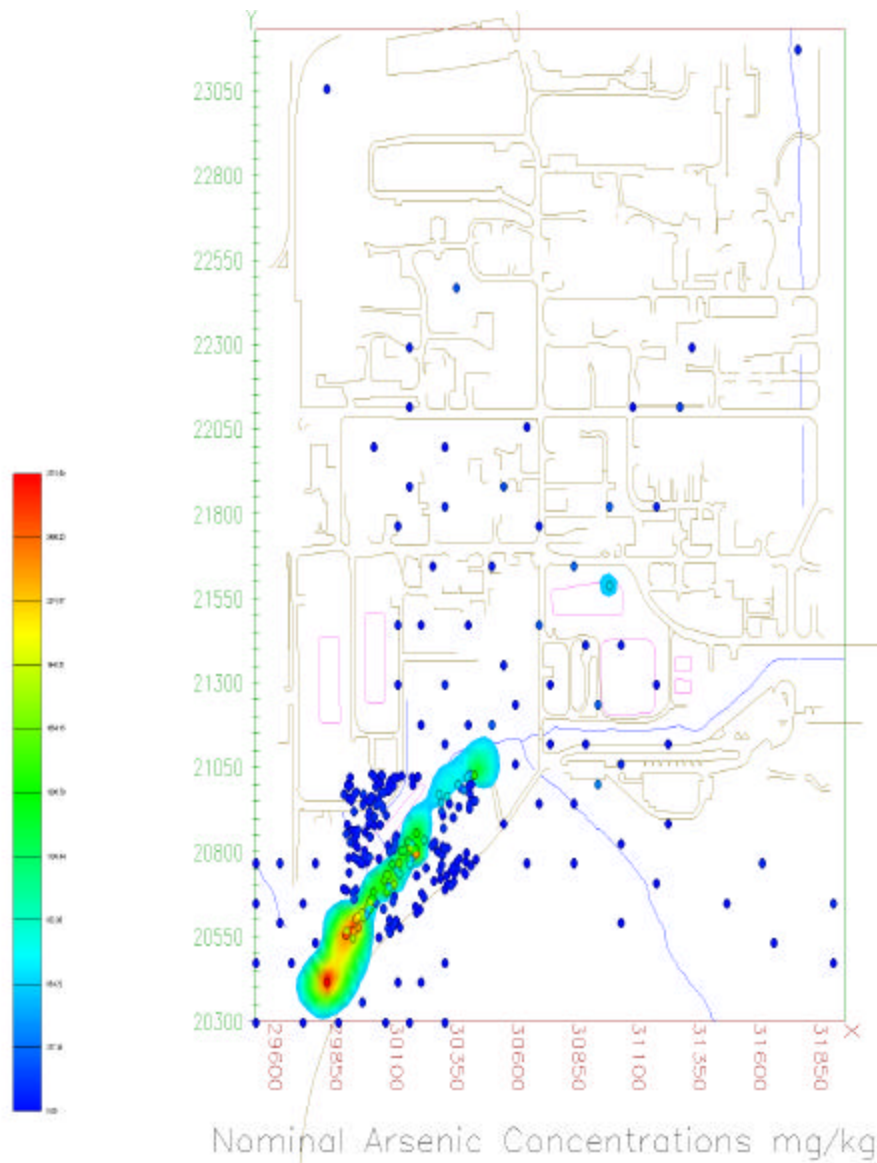


Figure 16. EVS-PRO representation of the Site N nominal arsenic contamination above the 500-mg/kg threshold after completion of the sample optimization analysis. Sample locations are depicted on the map as color-coded circles.

team took the data set used by EVS-PRO (original data plus 80 additional data points) and generated an arsenic contour map at the 125-mg/kg (blue) and 500 mg/kg (red) thresholds. This map is shown in Figure 17. Sample locations on this figure are marked by a diamond. Figure 18 presents the baseline analysis obtained using the entire data set (4187 points). The results shown in Figures 17 and 18 were generated using the Surfer software package and kriging for data interpolation. A comparison of Figures 16, 17, and 18 indicates that the EVS-PRO sample optimization procedure did a poor job of locating contamination at the site. EVS-PRO found only one additional region above the 500 mg/kg threshold (the region at the southwest corner was

part of the original data). The data, as depicted in Figure 18, indicate that several such regions exist. One region with high arsenic concentrations in the central part of the site that was missed by the EVS-PRO sample optimization process was several acres in area. EVS-PRO found about half of the regions with contamination above the 125 mg/kg threshold.

The poor performance of the sample optimization analysis was caused by the analyst's assumption that the contamination for the entire site was correlated to the data initially provided for a small section of the site and use of the default geostatistical parameters. EVS-PRO bounded the contamination in the southwest corner of the site and then selected

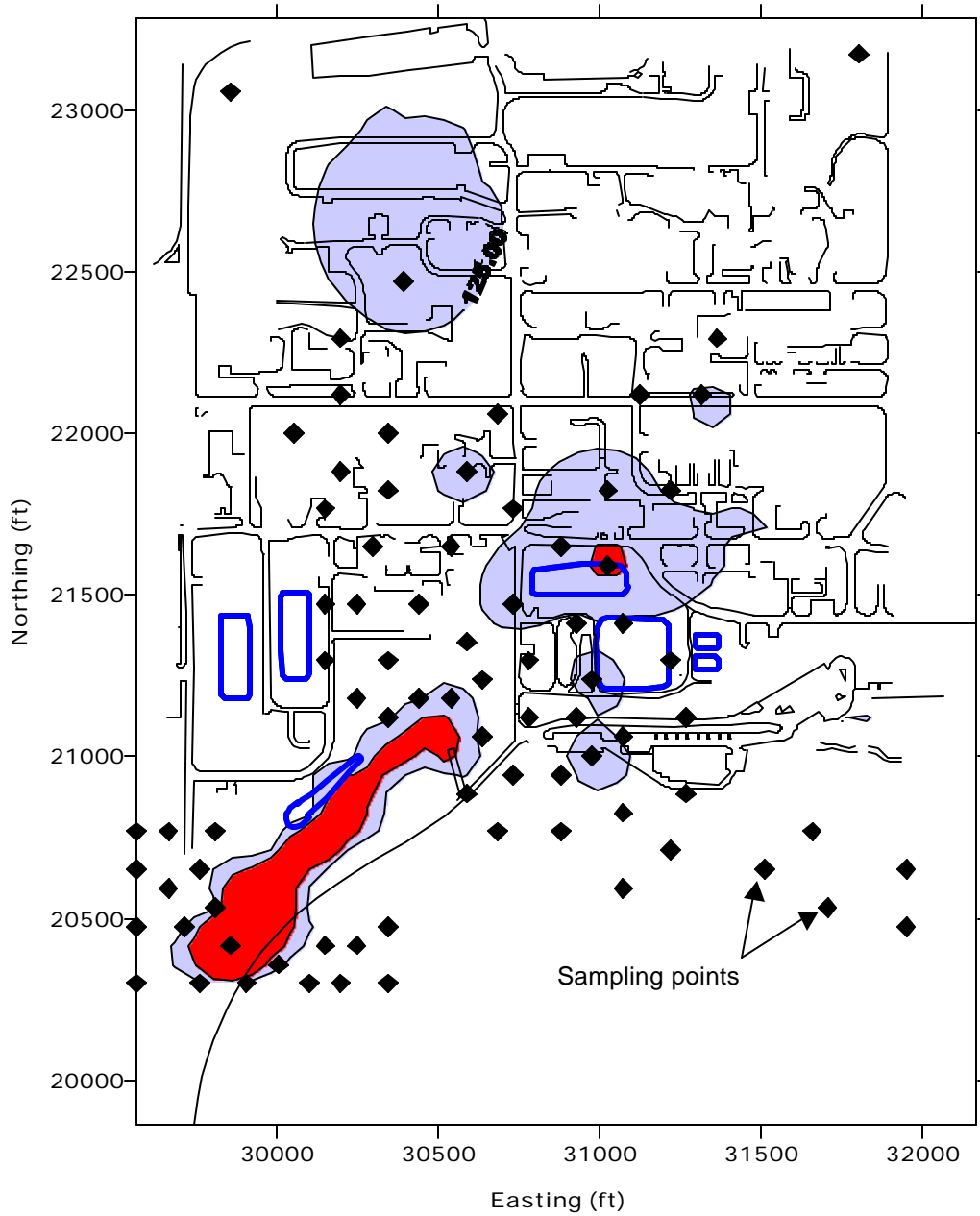


Figure 17. Surfer representation of the Site N nominal arsenic contamination above the 125- (blue) and 500- (red) mg/kg thresholds using the same data set as the C Tech analyst after completion of the sample optimization analysis.

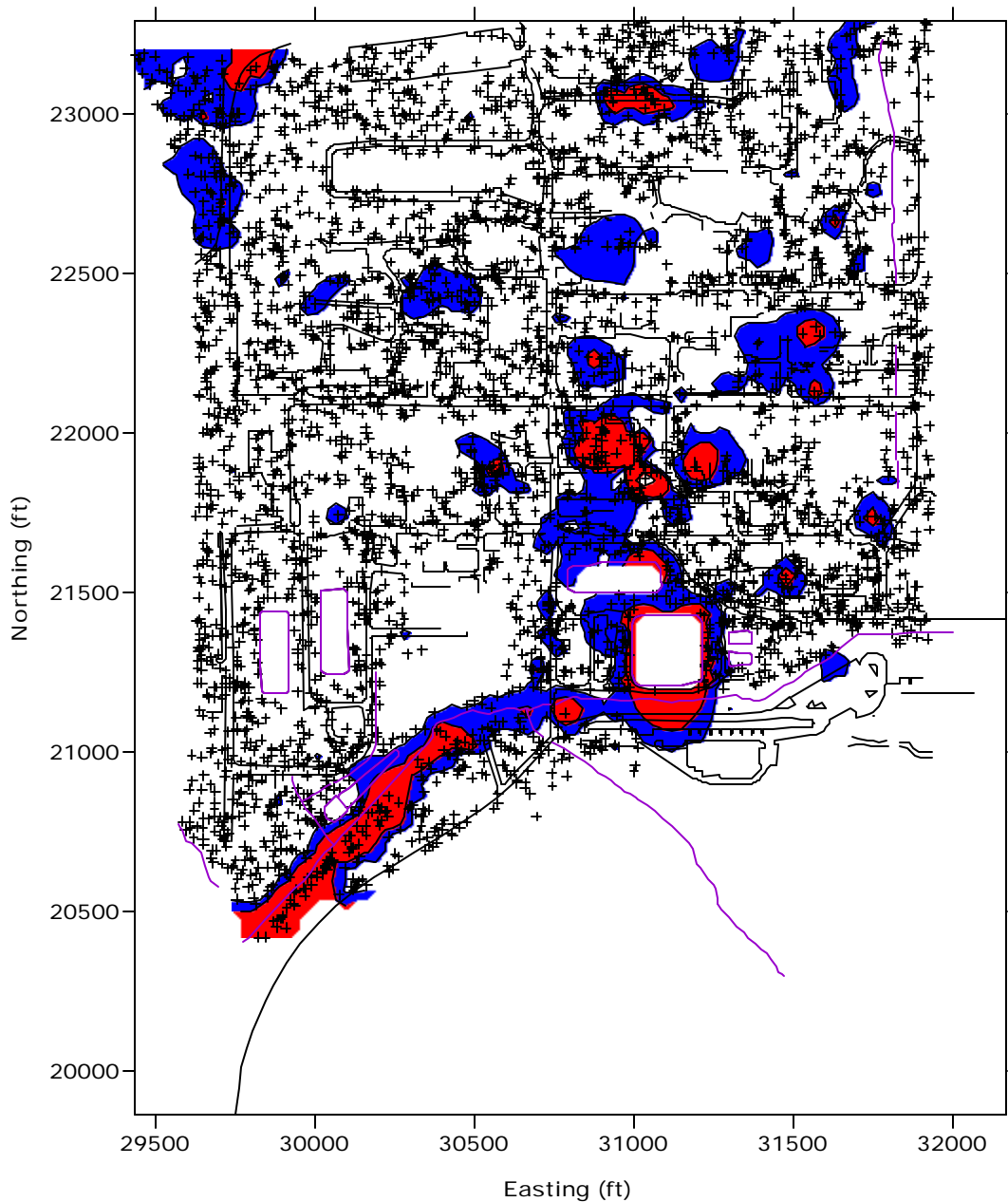
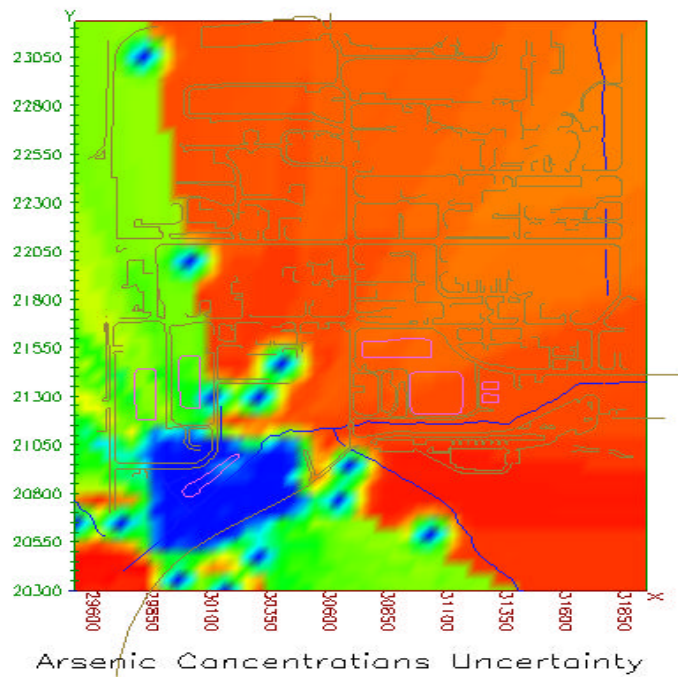


Figure 18. Baseline analysis of the Site N nominal arsenic contamination above the 125- (blue) and 500- (red) mg/kg thresholds using the entire data set (4187 points).

samples by moving a short distance from the measured data. The process was repeated in steps until the limit of 80 additional samples was reached. This meant that the analysis had very little data for large areas of the site. The result of this process is reflected in Figure 19, which shows two maps generated by EVS-PRO representing uncertainty at the start and at the finish of the sample optimization process. Uncertainty as used in EVS-PRO is a measure of the confidence in the predicted concentrations. Regions of high uncertainty generally require more data before the region of

contamination can be defined accurately. In Figure 19 red represents high uncertainty and blue represents low uncertainty. The top map represents the uncertainty based on the initial data plus the first set of 12 samples. The map indicates that there is large uncertainty throughout most of the site. The bottom map represents uncertainty after 80 additional samples and shows that the uncertainty has been reduced in the southwest corner of the site but still remains large in the northeast of the site. If more samples had been allowed, it is likely that adequate characterization would have been achieved.



EVS-PRO uncertainty maps

- Red = region of highest uncertainty
- Blue = region of least uncertainty

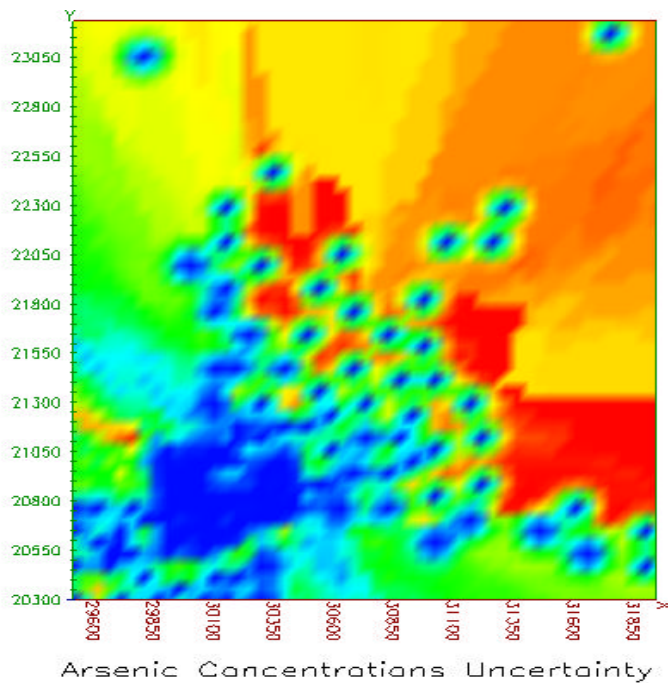


Figure 19. EVS-PRO-generated uncertainty maps for the Site N sample optimization problem. *Top*, uncertainty after the first round of sampling. *Bottom*, uncertainty after completion of a sample optimization limited to 80 additional data points.

EVS-PRO allows the user to override the default parameters to optimize the search strategy for locating additional samples based on the site-specific problem. Had this been done, it is likely that a better sample optimization scheme would have been obtained using only 80 samples.

The C Tech analyst also provided maps of the arsenic contamination at the 10% and 90% probability levels. They appeared to be almost identical to the 50% probability level map. This was surprising because of the high uncertainty levels represented in Figure 19. The similarity between the maps may have been due to the concentration scale used by the C Tech analyst, which did not focus on the thresholds specified in the problem of 125 and 500 mg/kg for arsenic.

Site S Sample Optimization and Cost-Benefit Problem

The Site S test problem involved CTC groundwater contamination. Initial data were provided for 24 locations as a function of depth. The analyst was also given hydraulic head data indicating that the flow in this region was approximately due south. In addition, a small vertical hydraulic gradient indicated that the water was sinking deeper as it moved from north to south. Maps of site features such as roads and buildings were not provided in this test case.

The C Tech analyst chose to perform the sample optimization in two dimensions. The analyst reasoned that if a well was drilled, data would be collected at all depths, thus providing a vertical profile of contaminant concentrations. Therefore, the analyst judged it pointless to attempt a 3-D optimization. The technical team agrees that this is a reasonable approach. Using the geostatistical routines in EVS-PRO to select sample locations, the C Tech analyst requested additional data at 15 locations to further define the plume. The technical team concluded that this was a reasonable number of samples for defining the plume using only geostatistics. However, optimization of the contouring parameters and use of the information about groundwater flow could have resulted in essentially the same information with fewer samples (10–12) than were used during the sample optimization process.

Using the final data set, EVS-PRO generated 2-D maps of the concentration distribution based on the maximum in each well and the probability of

exceeding the two threshold concentrations for CTC. Two-dimensional maps of the maximum (25% probability level), nominal (50% probability level) and minimum plume (75% probability level) were provided. Three-dimensional visualizations were also provided in VRML format to allow the user to navigate around the plume. The data were also used to generate a cost-benefit analysis of the contaminated area (2-D) and volume (3-D) vs cleanup threshold at the three probability levels.

The EVS-PRO 2-D 5- $\mu\text{g/L}$ contour map based on the maximum concentration in each well at the three different probability levels is shown in Figure 20. The 5- $\mu\text{g/L}$ concentration level is denoted by green; areas in red have concentrations above 100 $\mu\text{g/L}$. Sample locations are marked with a color-coded circle indicating the measured value at that point. This illustration highlights the differences in predicted concentration as a function of probability. The 75% probability plume (minimum) indicates much lower concentrations than does the 50% probability plume. However, the area of contamination in these two cases appears similar. The 25% plume (maximum) shows extensive spreading of the plume around the edges of the modeled domain where there are no data. This is a result of the kriging parameters used to determine the probability levels. The regions at the edge of the domain are not downstream from the source, and therefore, it is not probable that the contamination would occur in these regions.

Figure 21 presents the technical team's 2-D analysis of the CTC contamination at the 5- $\mu\text{g/L}$ (blue) and 500- $\mu\text{g/L}$ (red) levels for the maximum concentration in each well. This map was generated using the data set obtained by the C Tech analyst through the sample optimization process. Surfer was used to interpolate the data using kriging with an anisotropy ratio of 0.3. This value for anisotropy was based on the observed spreading of contamination in the direction perpendicular to flow and was optimized to provide the best match with the observed data through repeated kriging analysis. Comparison of the baseline analysis with the EVS-PRO nominal plume shows excellent agreement. The baseline analysis predicts that the plume migrates slightly further to the south (northing of 25000–25500 on the map). The slightly greater predicted area of the contamination is due to the value chosen for the anisotropy ratio, which spreads the predicted contamination along the direction of flow.

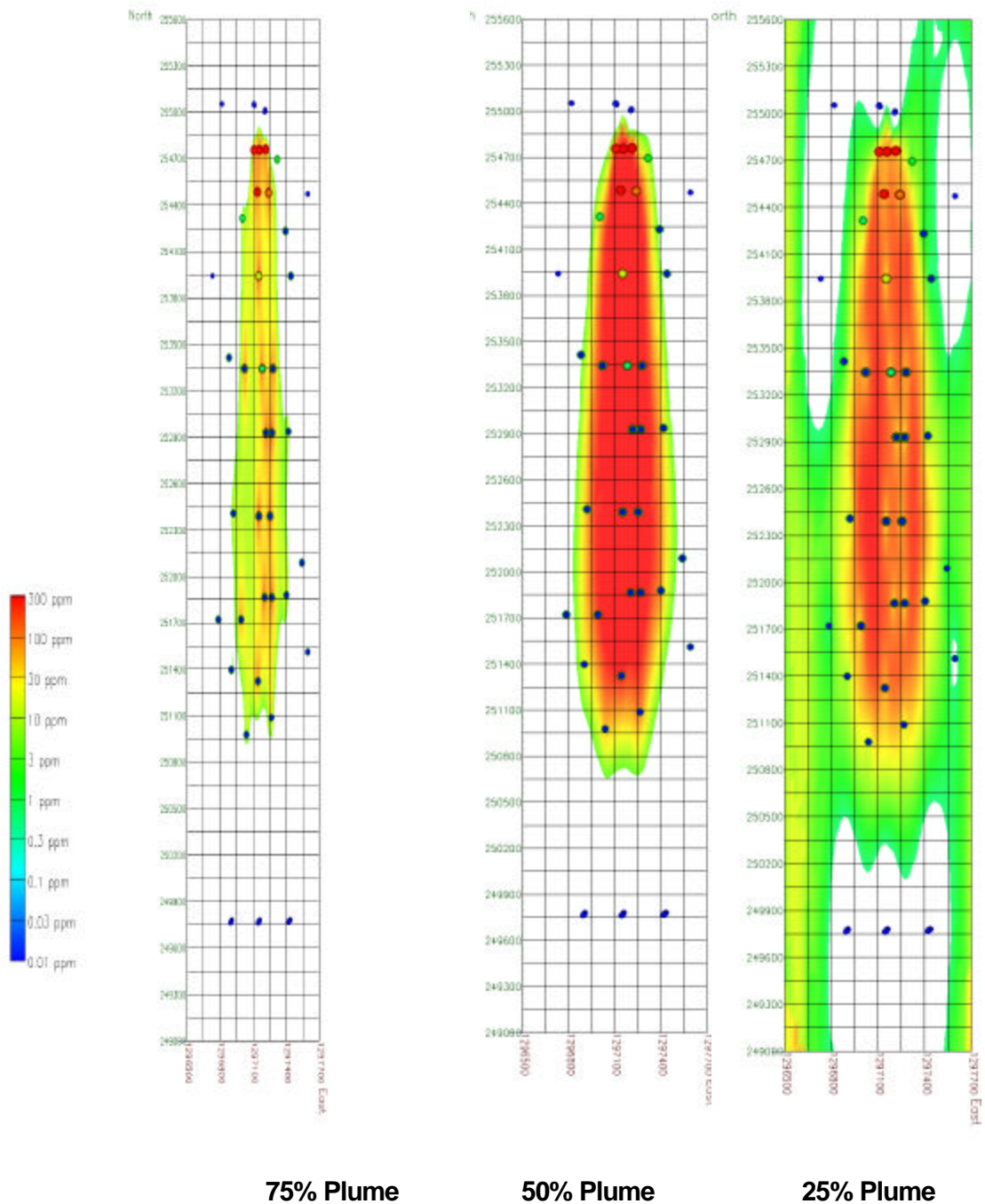


Figure 20. EVS-PRO 2-D representation of the Site S 75% (minimum), 50% (nominal), and 25% (maximum) probability CTC plumes above the 5- $\mu\text{g/L}$ threshold. Visualization is based on the maximum measured value (independent of elevation) in each well after completion of the sample optimization process.

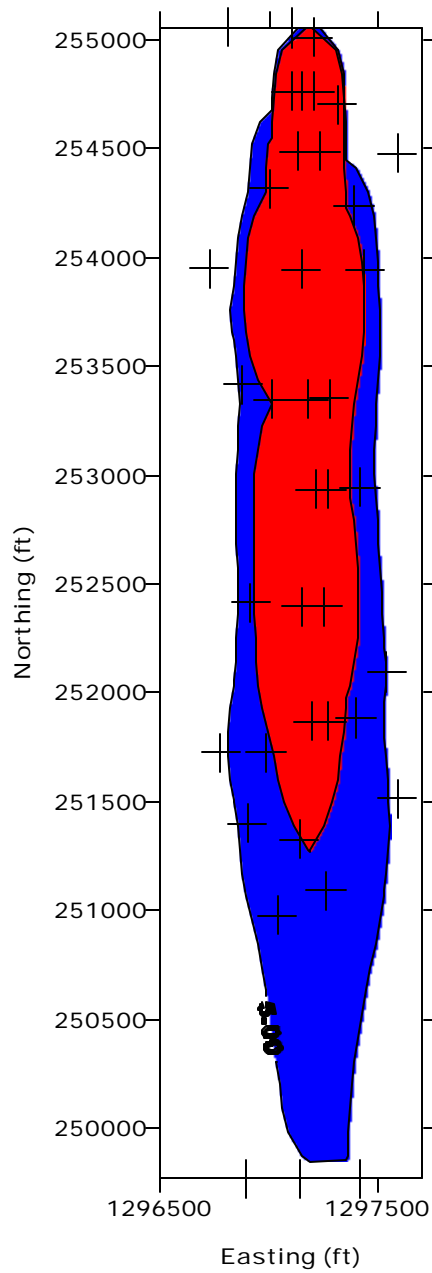


Figure 21. Baseline analysis of the Site S nominal CTC plume at threshold concentrations of 5 $\mu\text{g/L}$ (blue) and 500 $\mu\text{g/L}$ (red). The analysis was conducted using Surfer and the data set used by C Tech in generating its plume maps. The maximum value in each well was used for determination of the extent of contamination. Sample locations are marked with a +.

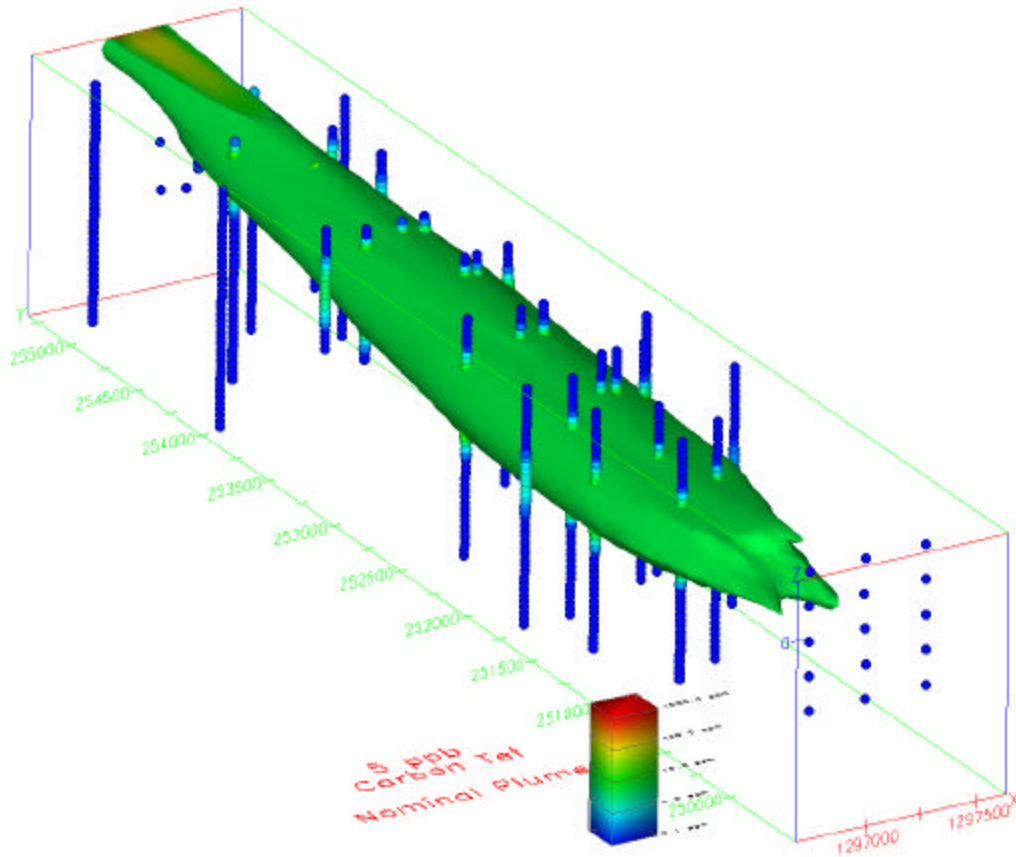


Figure 22. EVS-PRO 3-D visualization of the Site S nominal CTC plume above the 5- $\mu\text{g/L}$ threshold. Color-coded circles represent all measured data.

The EVS-PRO 3-D visualization of the nominal plume at 5 $\mu\text{g/L}$ is shown in Figure 22. The map indicates that the plume migrates deeper as it travels from north to south. This is consistent with the data. In most wells, data were collected at 5-ft intervals, as represented by the color-coded circles at each well location. Comparison of the color-coded representations of concentration with the measured data showed agreement between the two. This 3-D perspective adds further insight on the structure of the plume as compared to the 2-D view in Figure 20. The depth of contamination and the thickness of the plume are evident in this view. [Click](#) here to view a VRML file of the plume. Figure 22 is one view that can be obtained from the VRML file. The VRML file allowed the technical team to rotate the 3-D image and see the CTC contamination from different perspectives.

The C Tech analyst also provided estimates of the contaminated area and volume as a function of threshold concentration and probability level for

CTC. The technical team used the same data as obtained by C Tech through sample optimization and, using Surfer, estimated the contaminated area and volumes above the two threshold concentrations. Area and volume estimates as a function of probability were also obtained using GSLIB. Finally, the data for this test problem were developed from the analytical solution of a differential equation that represented contaminant transport in the aquifer subject to a constant CTC source. The analytical solution was used to estimate the actual area and volume of the contamination above the threshold concentrations. The use of Surfer, GSLIB, and the analytical solution provide a thorough baseline analysis for comparison.

While agreement between the EVS-PRO and baseline areal contaminant maps was good, comparison of the initially provided nominal (50% probability) area and volume estimates for the CTC plume provided by C Tech were in poor agreement at both threshold concentrations. The C Tech analyst was questioned about the differences and given the

opportunity to reexamine the calculations. Two separate operator errors were found in the calculations. For the volume calculations, the C Tech analyst indicated that the vertical axis was scaled by a factor of 5 for visualization. Volume calculations were performed on the scaled axis and therefore were a factor of 5 larger than they should have been. For the area calculations, the C Tech analyst stated that the parameters set to enhance sample optimization decisions led to poor estimates of the area. In this case, a “ceiling” was set such that all measured values greater than the threshold were set to the threshold value. This focuses the selection of the next sample locations to the regions on the outer edge of the plume and helps to define the plume boundaries with fewer samples. The initial area estimates were made using the ceiling limited values and not the actual values. This caused an under-

estimation of the actual plume size. After correcting for the operator mistakes in calculating the area and volume, C Tech supplied revised estimates for the area (Table 8) and volume (Table 9). The technical team estimates based on Surfer, GSLIB, and the analytical solution are also provided in these tables.

The revised EVS-PRO area estimates show very good agreement with the baseline analyses performed using GSLIB and Surfer and the analytical solution. For the 500- $\mu\text{g/L}$ threshold, the EVS-PRO area estimate is 45% less than the baseline GSLIB estimate and 25% less than the estimate based on the analytical solution. For the 5- $\mu\text{g/L}$ threshold, the EVS-PRO estimate is 12% less than the baseline GSLIB estimate and 15% less than the analytical solution estimates.

Table 8. EVS-PRO, baseline, and analytical estimates of the area of CTC contamination (ft^2) at Site S as a function of probability

Analysis	75% probability (min-plume)	50% probability (nominal)	25% probability (max-plume)
<i>CTC at 5 $\mu\text{g/L}$</i>			
EVS-PRO	1.6E6	2.3E6	3.6 E6
Baseline Surfer	—	2.8E6	—
Baseline GSLIB	1.2E6	2.6E6	4.1E6
Analytical	—	2.7E6	—
<i>CTC at 500 $\mu\text{g/L}$</i>			
EVS-PRO	1.4E5	9.3E5	1.7E6
Baseline Surfer	—	1.4E6	—
Baseline GSLIB	9.8E5	1.7E6	3.1E6
Analytical	—	1.2E6	—

Table 9. EVS-PRO, baseline, and analytical estimates of the volume of CTC contamination (ft^3) at Site S as a function of probability

Analysis	75% probability (min-plume)	50% probability (nominal)	25% probability (max-plume)
<i>CTC at 5 $\mu\text{g/L}$</i>			
EVS-PRO	9.8E7	1.5E8	2.2E8
Baseline Surfer	—	4.3E8	—
Baseline GSLIB	9.4E7	2.2E8	6.1E8
Analytical	—	1.6E8	—
<i>CTC at 500 $\mu\text{g/L}$</i>			
EVS-PRO	1.6E5	2.2E7	6.0E7
Baseline Surfer	—	5.5E7	—
Baseline GSLIB	2.9E7	5.2E7	7.3E7
Analytical	—	3.9E7	—

The technical team obtained volume estimates by generating 2-D plume maps as a function of depth at 10-ft intervals using the data obtained by C Tech through sample optimization. The area above the threshold was calculated for each of these vertical slices and converted to a volume by multiplying the area by the thickness of the layer. The volume of each layer was summed to obtain the total volume. This can be an acceptable approach for Site S because, unlike Site A, the site has no confining bedrock layer. Baseline volume estimates were obtained using Surfer and GSLIB. The baseline results, the analytically calculated volume, and the EVS-PRO estimates are presented in Table 9. The EVS-PRO estimates show excellent agreement with the analytical solution and the Surfer and GSLIB baseline estimates for the nominal plume volume at both threshold concentrations. For the nominal plume (50% probability) the EVS-PRO volume estimates are 6% lower than the analytical estimate at the 5- $\mu\text{g/L}$ threshold and 43% lower than the analytical estimate at the 500- $\mu\text{g/L}$ threshold.

For the 5- $\mu\text{g/L}$ CTC threshold concentration, the EVS-PRO 25, 50, and 75% probability level volume estimates show reasonable agreement with the baseline GSLIB estimates. Estimates between the two approaches match almost exactly for the minimum plume (75% probability) and differ by a factor of 3 for the maximum plume (25% probability). The range in EVS-PRO plume volumes, from the minimum ($1 \times 10^8 \text{ ft}^3$) to the maximum ($2.2 \times 10^8 \text{ ft}^3$), includes the baseline analytical volume of $1.6 \times 10^8 \text{ ft}^3$. For the 500- $\mu\text{g/L}$ CTC threshold value, the EVS-PRO volume estimates at the 25 and 50% probability levels are less than the baseline GSLIB estimates by factors of 0.8 and 0.4, respectively. At the 75% probability level, the EVS-PRO estimate is 1/180 of the baseline GSLIB estimate. The 75% probability level is the volume over which there is at least a 75% chance that the contamination will exceed the threshold concentration. The 75% probability level EVS-PRO estimate for the 500- $\mu\text{g/L}$ CTC threshold value is extremely low and inconsistent with the baseline data, the baseline analysis, and the analytical solution. Upon review of the volume estimates, C Tech also provided a secondary method of estimating contaminated volumes. In this case, the EVS-PRO adaptive gridding model was used. This model places more computational elements in regions where concentrations are changing most rapidly. This should lead to a better volume estimate. The use of adaptive gridding did

not lead to major changes in the nominal plume (50% probability) or the maximum plume (25% probability) volume estimates. It did, however, substantially increase the estimate for the minimum plume (75% probability) to a value of $8.1 \times 10^6 \text{ ft}^3$. This volume is a factor of 4 lower than the baseline GSLIB estimate and more consistent with the data.

Based on the comparison of the final EVS-PRO area and volume estimates with the analytical solution and baseline estimates, the technical team concluded that EVS-PRO accurately calculated these quantities for this problem. However, initial EVS-PRO estimates provided by C Tech were not a good match to the baseline estimates. The cause of the discrepancy was determined to be two separate operator errors. This indicates that the EVS-PRO analyst must be familiar with the operation of the software to obtain the proper area and volume of contamination estimates.

Site T Geology Interpretation

For the Site T problem, rather than perform another analysis of the extent of contamination (similar to the analysis performed for Sites A, B, D, and S), C Tech used EVS-PRO to analyze subsurface stratigraphy. The subsurface stratigraphy at Site T is characterized by many thin layers of different soil types, including clays, silt, silty-sand, sand, and gravel. The soil boring data were used to generate a 3-D animation of the subsurface stratigraphy. The animation rotated the viewing angle of the soil structure through 360° to provide a more complete view of the layers. The animation also provided an exploded view (layers separated slightly) to allow visualization of regions where the different layers pinch out (i.e., where the layer has zero thickness). Figure 23 provides an exploded view of one perspective from the animation and contains the various subsurface layers as identified by the key. Pinching out of the different layers is clearly shown in the figure. Coordinate data, including elevation, are provided as a frame of reference. [Click here](#) to view an animation generated using EVS-PRO. The technical team evaluated the animation as well as supporting visualizations provided by C Tech. The boring well locations were marked on some of the supporting visualizations, and this helped in checking the visualizations. The review demonstrated that the location of the geologic layers matched the data at sample location points. Each layer in the C Tech animation was consistent with the data provided for the analysis.

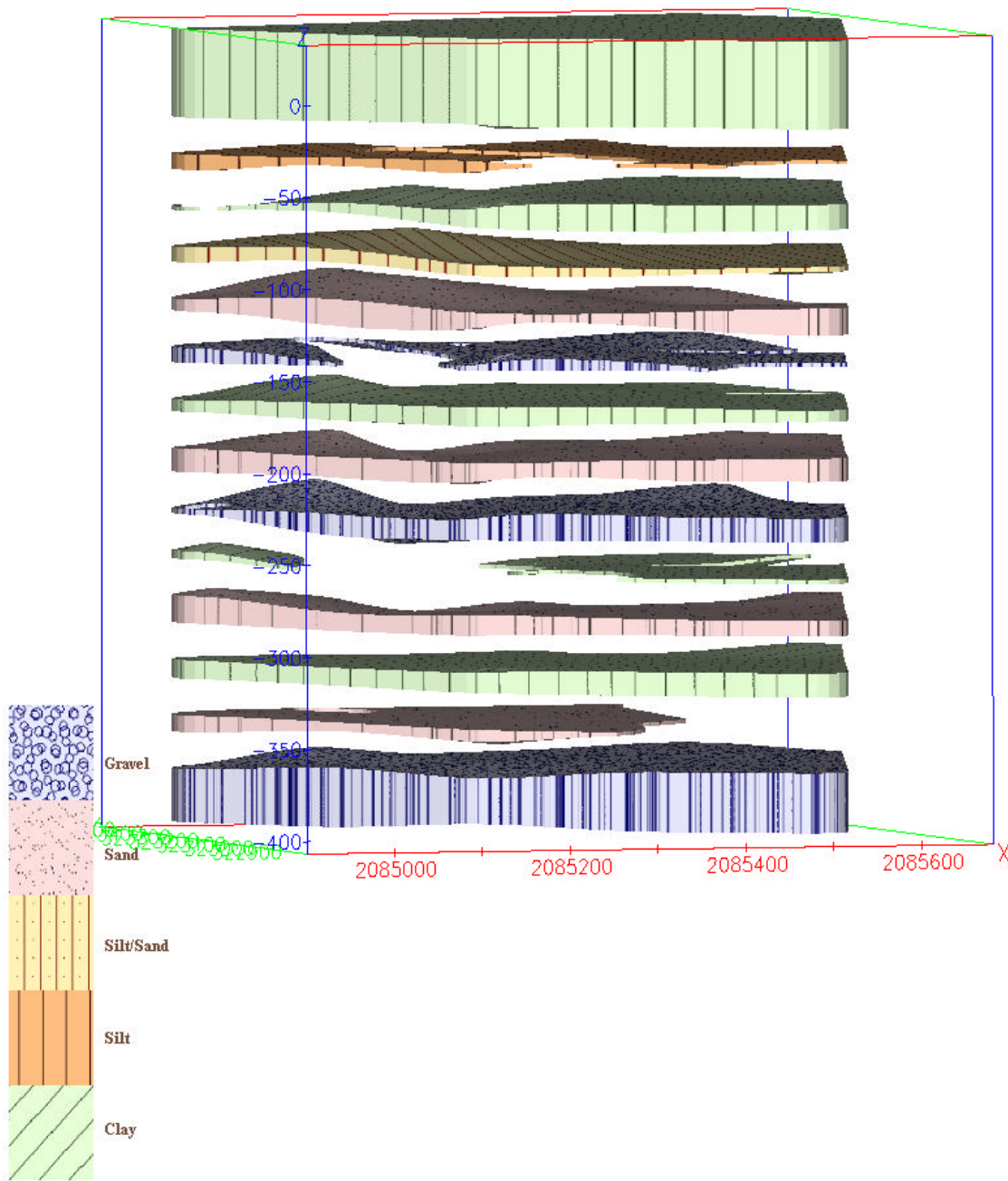


Figure 23. EVS-PRO 3-D exploded view of the Site T subsurface stratigraphy. Soil types are identified in the key at the left of the figure.

In addition to the animation of subsurface stratigraphy in Figure 23, C Tech demonstrated EVS-PRO's ability to generate another depiction of the Site T subsurface using 3-D indicator kriging of the subsurface data. The geologic indicator kriging feature of EVS-PRO is a powerful geospatial tool that provides multiple lines of reasoning for interpreting subsurface soil or geologic information. Figure 24 presents the results from the 3-D geologic indicator kriging for Site T. [Click here](#) to view the 3-

D animation. The result of the 3-D kriging of layers allows for better representation of the subsurface layers at unsampled locations and provides a better representation of regions that transition from layer to layer. The technical team evaluated the kriging parameters and the results presented in Figure 24 and concluded that the subsurface data is adequately represented and that the EVS-PRO depiction is consistent with the data provided.

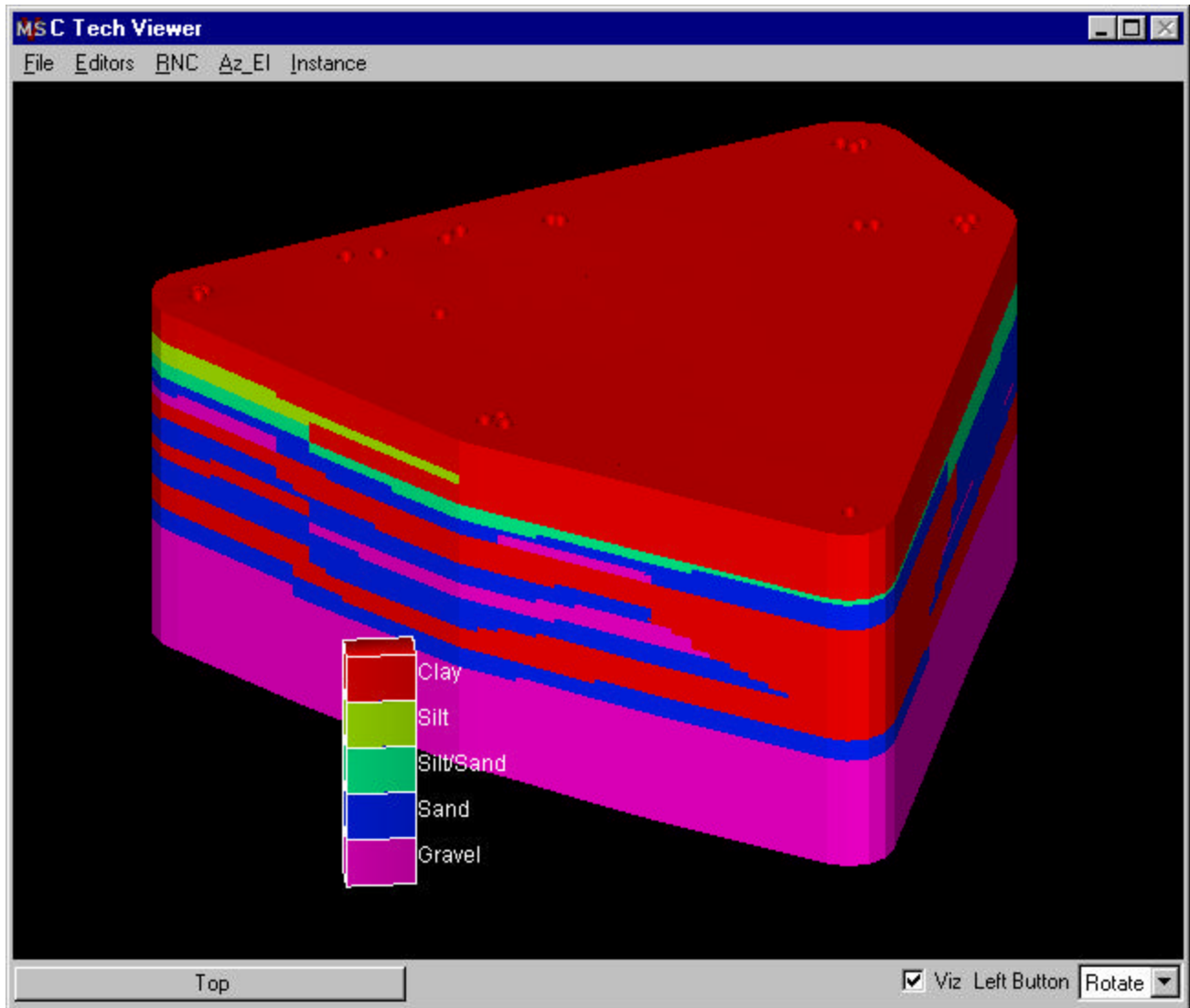


Figure 24. EVS-PRO depiction of Site T subsurface stratigraphy based on indicator kriging modeling of soil layers. Soil types are identified in the key at the left of the figure.

Multiple Lines of Reasoning

The C Tech analyst used EVS-PRO to perform geostatistical analysis with the data. This information provided a quantitative measure of the probability of exceeding threshold concentrations and allows the decision maker to judge the effects of uncertainty on the decision. Although EVS-PRO automates selection of contouring parameters and sample optimization locations, the operator is able to override the default values to optimize these functions for the problem under study. Selection of a particular scheme depends on the objectives of the analysis and the amount of data. EVS-PRO provides the capability to examine subsurface stratigraphy by use of different interpolation algorithms, as demonstrated on the Site T problem. In addition,

EVS-PRO provides multiple visualization options that assist in understanding the nature and extent of contamination problems.

Secondary Evaluation Criteria

Ease of Use

EVS-PRO is a complex software package containing over 150 modules. To assist the user, EVS-PRO contains a graphical user interface (GUI) that accesses all of the features and modules. The EVS-PRO network editor, which is part of the GUI, uses object-oriented programming and allows the user to select and link all of the modules necessary for the simulation. The GUI and the drag-and-drop features of the network editor make EVS-PRO easy to use. An example of a network application is presented in

Figure 25. Modules at the top of the screen in this figure can be dragged into the lower part of the screen and connected to other modules through mouse operations.

The GUI provides a platform for addressing problems efficiently and for tailoring the analysis to the problem under study (e.g., contours at certain threshold concentrations). EVS-PRO stores alphanumeric data using an open database connectivity (ODBC) protocol. This database structure permits queries on any field (e.g., chemical name, date, concentration, and well identifiers) and

also permits filtering (e.g., to include only data within a range of elevations or to include selected data points).

EVS-PRO can import and export text and image files in a number of formats. Image files can be imported in drawing exchange format, ESRI shape file format, bitmap, or .jpg format. Output files can be produced in all of these formats and as animation (.avi) and VRML (.wrl) files. One limitation of EVS-PRO is that it requires alphanumeric data to be provided in a fixed order. Consequently, in the demonstration, the analyst imported the data into

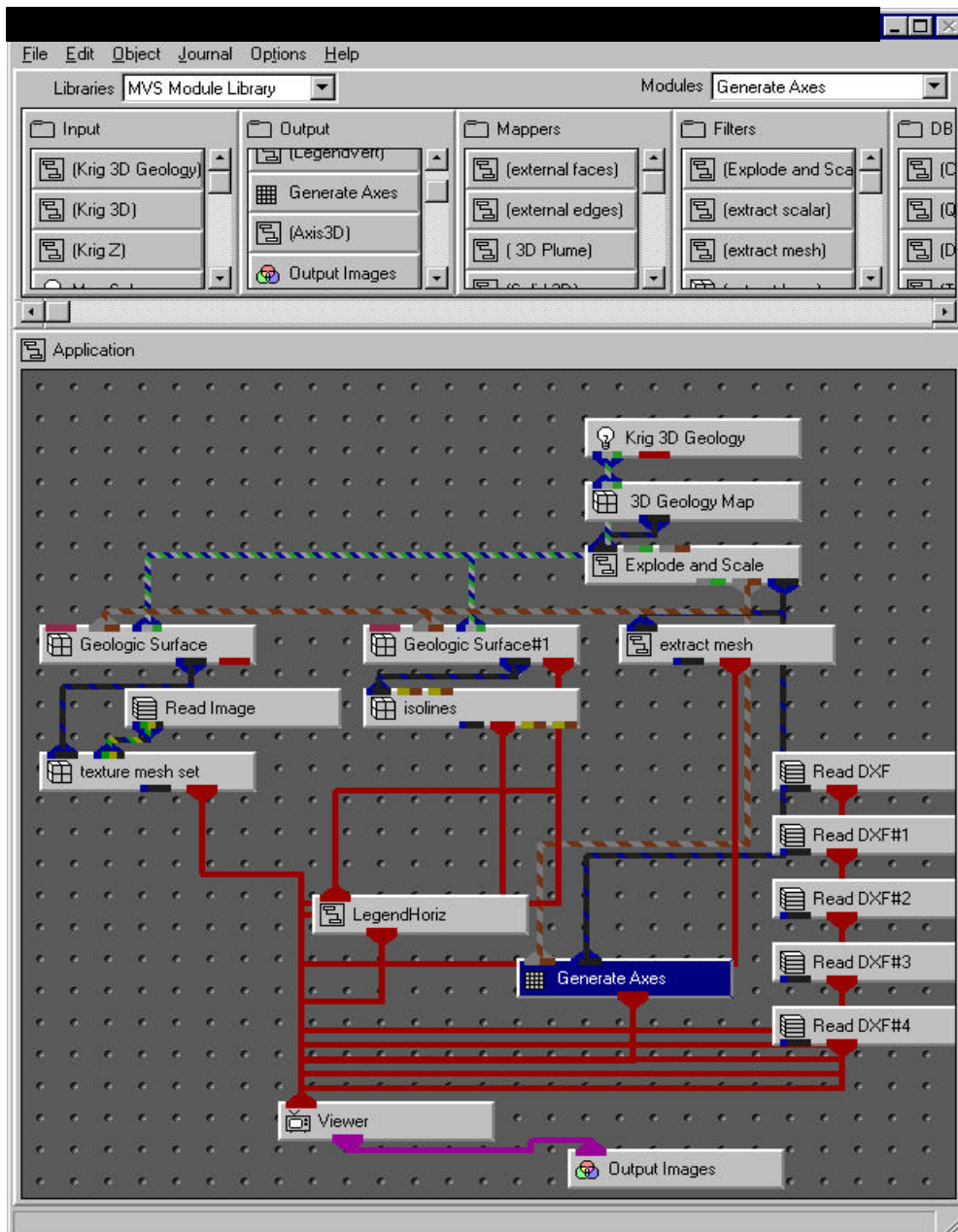


Figure 25. An example of the EVS network editor illustrating connection of different modules.

Excel, sorted the data into the structure required by EVS-PRO, and saved the file in ASCII comma-delimited format (.csv) before using it in EVS-PRO. Reorganizing the data was a major task in the demonstration. This limitation has been removed in subsequent versions of EVS-PRO.

During the demonstration, several members of the technical team received a 4-hour introduction to EVS-PRO. The reviewers found that EVS-PRO was a large, feature-rich software program that has an extensive on-line manual with case studies to guide the novice user through the system and applications. The reviewers concluded that with one or two days of training, they would be able to use the fundamental features found in EVS-PRO. However, it is clear that more training and regular use of the product would be needed to use all of the features found in the product efficiently. In particular, a larger investment of time would be required to learn to use the scripting language that permits automation of repetitive processes. The reviewers were impressed with the object-oriented structure of the code, which permitted linking of the various modules for an analysis.

Efficiency and Range of Applicability

EVS-PRO was used for four complete problems (three sample optimization/cost-benefit problems and one cost-benefit problem) and two partial problems (visualization of the initial data for one sample optimization problem and one geology interpretation problem) with 8 person-days of effort. Approximately four days were spent analyzing the data and another four days preparing the report. EVS-PRO processed a large amount of data and produced a large number of visualizations in a wide range of formats in a very short time. This was made possible primarily because of the automation and scripting features available in EVS-PRO. EVS-PRO provides the flexibility to address problems efficiently and to tailor the analysis to the problem under study. Databases can be queried and information processed by any field in the database (e.g., plot only TCE contamination over one sampling period). Although default parameters are available for most operations, the user has control over the choice of the parameters that control the geostatistical simulations. In addition, a wide range of environmental conditions (e.g., multiple contaminants, different media such as groundwater or soil, complex subsurface stratigraphy) can be evaluated. EVS-PRO should be applicable to

almost any soil or subsurface contamination problem.

Training and Technical Support

C Tech provides an extensive users' manual documenting code operation and use. The manual discusses the general framework used by EVS-PRO, construction of models using the object-oriented network approach, input parameters for each of the models, and examples of model applications. Self-paced training modules are available as part of the software package. Technical support is supplied by telephone and through e-mail. Training courses are available throughout the year. Software updates are available over the Internet.

Additional Information about the EVS-PRO Software

To make efficient use of the basic features in EVS-PRO, the operator must be familiar with contouring environmental data sets and managing database files. To use the advanced geostatistical features, the operator should also be knowledgeable in this area.

During the demonstration, EVS-PRO was run on a Windows 95 operating system. The computer used for the demonstration was a Pentium II 400 with a Titan II graphics card, 128 MB of RAM, a 4 GB-hard drive, and a 20X CD (read only).

EVS-PRO, the C Tech product used in the demonstration, sells for \$9995 for a single license. The pricing structure for EVS depends on the product selected and the number of licenses purchased. A detailed description of software products and prices is provided in Section 2 of this report.

Summary of Performance

EVS-PRO's performance is summarized in Table 10. The technical team concluded that the main strengths of EVS-PRO are its outstanding 3-D visualization capabilities and its capability to rapidly process, analyze, and visualize data. The capability to produce true 3-D data analyses and visualizations under conditions of complex subsurface geological characteristics and distribution of contaminants is important. The range of visualization output formats and their quality define EVS-PRO as a premier, state-of-the-art visualization system. The ability to sort and query the data and write scripts to automate repetitive tasks permits EVS-PRO to examine large amounts of data and quickly generate analyses and visualizations of the data. EVS-PRO's object-

Table 10. EVS-PRO performance summary

Feature/parameter	Performance summary
Decision support	EVS-PRO provides decision support through 3-D visualization of environmental data such as contaminant concentration contours, quantifying uncertainties in interpolation predictions, recommending additional sample locations to reduce uncertainties, and providing statistical information about the extent of contamination.
Documentation of analysis	A detailed report documented the technical approach, assumptions, and parameters used in the analysis.
Comparison with baseline analysis and data	EVS-PRO produced analyses and visualizations from six different sites. Visualizations included 3-D representations of geologic structure, hydraulic head, concentration contours above threshold values, and uncertainty maps. All the visualizations were consistent with the data. The visualizations accurately incorporated maps of surface features (roads, buildings, water bodies) and aerial photographs when available. Visualizations often provided well and sample locations as a function of elevation. Sample locations were accurately color-coded to match the measured data. Sample optimization was performed for Sites B, N, and S. The analyses for Site B and S adequately characterized the plume with an acceptable number of additional samples. The Site N analysis, which limited the number of samples, inadequately characterized the extent of contamination, a result of the use of the software's default parameters for spatial correlation modeling. Cost-benefit analysis of the volume of contamination as a function of threshold concentration and probability were provided for Sites A, B, N, and S. Volume estimates were often a poor match to the baseline analysis. Once again, this is due to the use of EVS-PRO's calculated default values for interpolation of data and selection of boundary conditions for spatial modeling. Volume estimates for plume extent at low-probability levels were typically greater than the baseline estimate by a factor of 3 or more.
Multiple lines of reasoning	EVS-PRO provides a number of different approaches for visualizing and examining the data, including control over essential modeling parameters. This flexibility permits multiple analyses of the data. EVS-PRO generates statistical information about the extent of contamination that assists in data evaluation.
Ease of use	EVS-PRO is a sophisticated software product with over 150 modules. The use of visual programming to link the modules makes use of EVS-PRO fairly easy. Most environmental analysts would be able to use the major features of EVS-PRO after two days of training. Advanced features such as use of the 3-D kriging of data sets and use of scripting language would require more training. An ease-of-use inconvenience is EVS-PRO's requirement of a fixed data field format. Enhancements to current versions of EVS-PRO have removed this limitation.
Efficiency	EVS-PRO efficiently imported, analyzed, and visualized environmental data sets. The program was used to analyze four complete problems (three sample optimization/cost-benefit problems and one cost-benefit problem) and two partial problems (visualization and geology interpretation) with 8 person-days of effort.
Range of applicability	EVS-PRO is a flexible tool in which the operator can define the modeling parameters so as to tailor the analysis and visualization to almost any problem involving contamination in soils or groundwater.
Training and technical support	Users' manual On-line help with guidance on parameter selection Technical support and training courses available for a fee Free Web-based support, including tutorials and documentation
Operator skill base	To efficiently use the basic features of EVS-PRO, the operator must be familiar with contouring environmental data sets and managing database files. To use the advanced geostatistical and statistical features, the operator should be knowledgeable in these areas.
Platform	Windows 95, 98, NT
Cost	\$9995 for a single user. The EVS pricing structure depends on the product and number of licenses sold to the customer. Discounts are available to educational institutions.

oriented programming structure allows the many modules to be easily linked together to perform a complex analysis.

EVS-PRO is a mature software system that does not have any major limitations. A minor ease-of-use limitation of EVS-PRO is the need to structure the data in a fixed order. This often requires the analyst to take an existing database and reformat it. Current versions of EVS-PRO allow the user to directly query ODBC compatible databases from within EVS-PRO for the purpose of creating input files in EVS format representing both geology and chemistry data.

EVS-PRO can perform sample optimization analysis recommending sampling locations and cost-benefit analysis of contaminated volume as a function of probability. To assist the analyst, EVS-PRO calculates values for the essential parameters used in these analyses based on the data. While the use of these calculated default values makes it easier for the analyst, it was observed that the values were not

always optimal for the sample optimization or cost-benefit analysis. In particular, for the Site N sample optimization problem approximately a third of the site remained unsampled because of the approach used in EVS-PRO and the limit on the number of samples. For the cost-benefit problems, the estimates of contaminated volumes were often a poor match to the baseline analysis. This was especially true for the low-probability plume volume estimates, where use of the default parameters often caused the program to predict contamination in regions upstream from the main plume that did not contain data. The test team concluded that operator intervention to optimize geostatistical model parameters would have led to better, more accurate analyses. The problems identified are a function of the operator, not the software, and emphasize the need to have qualified analysts operate the software and for the analyst to examine the model outputs for consistency with the data. The C Tech analyst effectively provided a first iteration to conducting an analysis, thus emphasizing the analysis and visualization capabilities of the EVS-PRO software.

Section 5 — Environmental Visualization System Update and Representative Applications

Objective

The purpose of this section is to allow C Tech Development Corporation to provide information regarding new developments with EVS-PRO since the demonstration activities. In addition, C Tech Development Corporation has provided a list of representative applications in which its technology has been or is currently being used.

Technology Update

The EVS suite of products is continually evolving and improving. Since the demonstration, a number of changes have been made to EVS products. The following lists the changes with a brief description of their function. For complete information contact C Tech at www.ctech.com.

New Interfaces

EVS for ArcView extension (which requires ESRI's ArcView Version 3.1 or later) has been developed. This ArcView extension is available for use (at no cost) to all C Tech customers. It provides an environment to create EVS chemistry and geology files from within ArcView and to launch any version of C Tech software from within ArcView. This extension was developed to provide a more user-friendly environment for casual (or less experienced) users and to support the newest version of EVS, EVS for ArcView. This interface removes the limitations of fixed-format input identified in this report.

Enhanced Modules

The following enhancements are now available:

- New input and output ports to all modules that read ASCII geology or chemistry input files.
- New features for the Viewer, including a new pull-down menu called "Instances," which automatically connect a few frequently used modules.
- An enhanced Light Editor that improves surface topography visualizations.
- Dramatic enhancements to the animator to allow control of virtually any EVS/MVS parameter without editing of the animation script file.

- Support in many modules for input of exponential values.
- Modifications to the Volume_Render module for better default values for software rendering.
- Enhancement of 3D_Geology_Map module to perform automatic distribution of cells into model layers based on the average thickness of each layer.
- Modifications to the "cut" module to allow for the cutting to be based on an externally input slice plane. The user can displace the cutting surface any distance from this external plane. With two cuts, the user can create a region of any width that is centered around an external slice. Using slice_horizontal, slice_easting, or slice_northing (all of which can also be rotated), as input, the operator can have much more control over cutting. In addition, the rightmost output port of "cut" now outputs the "other half" of the model. This is useful for displaying a solid model on one side of the cut model and a plume on the other.
- True 3-D text which utilizes any of the True Type fonts installed on a computer. Three-dimensional text objects are filled polygons with no thickness or true 3-D solid objects (with optional beveled edges). The new fonts will be available in the Titles module, Color_legend, Map_Spheres, and Generate_Axes.
- The ability to assign specific user-defined colors to individual objects (like geologic layers).
- Enhanced single and multi-range datamap editing.
- Nonlinear interpolation in the Animator.
- Multi-range data maps that are saved with applications.

New Modules

EVS and MVS have been upgraded by the addition of a number of new modules to perform specific tasks during data processing, analysis, and visualization. Two of the more important modules are as follows:

- MVS now includes C Tech's version of the Stanford GSLIB 3-D kriging routine, KT3D, which has enhanced functionality. The MVS

gridding capability combined with a user-friendly Windows interface is a major improvement over the Stanford GSLIB version.

- Four new modules (Animate_Field, Animate_UCD, Animate_netCDF, and Animate_netCDF_Explode) are the foundation for the newest product, MAS. These modules—in MAS, EVS-PRO, and MVS—are complex macro modules that incorporate the functionality of several modules and integrate a customized looping function that allows for creating interpolated time sequences of frames to produce animations.

In addition, modules have been written to

- create bitmap files containing spatial reference information; this module can be used to prepare a georeferenced image that can be imported by ArcView and other GIS applications;
- create a top view of the site;
- import and display image files (e.g., bitmap files);
- provide a simple means to add the numerical output from up to four input ports, with the capability of editing this module's expression to perform subtraction or other math operations;
- subdivide triangular and quadrilateral cells until none of the sides of the output triangles exceed a user-specified length;
- create the fundamental geologic grid information to a file format that Ground Water Vistas can read, including x,y origin, rotation, and $x-y$ resolutions in addition to descriptive header lines;
- optimize output for Open_GL rendering;
- create slices in the vertical, easting, or northing planes and manipulate their positions interactively;
- create 3-D buildings directly in EVS/MVS without using computer-aided design (CAD) programs;
- cut a cylindrical cross-section tunnel along a 3-D polyline path;
- configure and set default values for most key modules and default data paths, allowing the user to add project- or user-specific settings in EVS, EVS-PRO, and MVS; and
- create additional animation files (including AVI, MPG, and HAV).

Representative Applications

The following companies have provided brief descriptions of the work that they have performed using C Tech's visualization software (EVS-PRO and MVS). A short discussion of each project follows. For more information contact C Tech or the user company at the web address provided.

Research Triangle Institute (RTI)

www.rti.org

RTI used EVS-PRO to develop

- animated visualizations of the migration of a chlorinated solvent plume for an industrial facility in the southeastern United States. This visualization supported the development of a monitored natural attenuation corrective action, saving the client hundreds of thousands of dollars in potential cleanup costs.
- visualizations of the geology and water levels within heavily used aquifers in the Atlantic coastal plain. RTI showed that water-level declines in many areas exceed the natural recharge of the water-supply aquifers, potentially leading to problems with decreasing groundwater supplies, saltwater encroachment, and land subsidence.
- animated visualizations of the advance of an open-pit mine in the Atlantic coastal plain. The complex geologic data included 19 geologic units in addition to the ore. The animations showed the projected development of the mine through ten years. The visualizations effectively demonstrated technical mining geologic data to upper-level management and to other stakeholders in the mining operation.
- analyses of ore-quality data using 3-D geostatistics to determine the distribution of a series of ore-quality parameters and also to project the variability in the ore quality associated with future mine development.

U.S. Department of Energy, Grand Junction (Colorado) Office (DOE-GJO)

DOE-GJO used EVS-PRO to

- model and map contaminant plumes and tank structures in the high-level radioactive waste tank farms at the Hanford facility;
- map surface and subsurface topography and geologic structure for the Uranium Mill Tailings

Remedial Action (UMTRA) Ground Water project; and

- provide visual representation of various surface and subsurface geophysical surveys done by DOE-GJO.

Walden Associates, Inc.

www.walden-assoc.com

Using EVS software, Walden Associates created a 3-D animation that illustrated subsurface conditions at an airport below the runway deck and adjacent taxiway. The intent of the animation was to illustrate the depth and number of required structural pilings proposed for construction. The 3-D model was rotated and probed to show subsurface conditions throughout the proposed construction area. The animation was finalized with aerial photographs, a 3-D pile driver, and aircraft for location and scale. The final movie file was presented to the port authority on a VCR tape for in-house presentations.

URS Greiner Woodward Clyde (URS)

www.urscorp.com

URS used EVS-PRO to

- support a case for natural attenuation of a groundwater plume at a former manufactured gas plant site in southeastern Pennsylvania. The presence of nonaqueous phase liquids (NAPLs) and unremediated source areas threatened the viability of this approach. An animated video demonstrating plume stability was created in EVS-PRO from the actual results of eight rounds of quarterly monitoring. After the video was presented to the regulators, subsequent site closure discussions focused on the positive aspects of plume stability, rather than on the negatives of undefined NAPLs or unremediated sources. The results achieved with the full-motion video could not have been achieved with conventional tabular or graphic output.
- depict the proposed configuration and construction of a new subway in a major U.S. city. The animation produced in EVS-PRO was an effective means of showing existing and developing subsurface information, existing facilities, and proposed design and construction concepts to the management team and to outside third parties interested in or affected by the project.
- generate an animation that illustrates the monitoring well network associated with a groundwater pump and treat system and the

effectiveness of the remediation over time. The animation begins by displaying the original extent of the groundwater plume and then shows how the plume regressed over time in response to the pumping.

- generate an animation depicting the results of a preliminary geotechnical investigation for a power generation facility. The animation shows proposed structures and the layout of the property to enhance an understanding of how the geologic conditions beneath the site may influence the type of foundations needed for each structure. Based on the locations of the structures and the underlying thickness of the clay unit, locations for additional geotechnical borings were proposed.
- generate an animation to present the natural attenuation remediation strategy over a 20-year period at a chemical facility in Pennsylvania. The extent of the groundwater plume in the lower water-bearing unit was depicted from a combination of actual groundwater quality data (1990–95) and modeled predictions (from Modflow/MT3D) to project the extent of the plume until the year 2009.
- generate an animation to illustrate the potential cost savings of drilling piles into a shallower sand unit rather than the proposed deeper sand unit. The animation shows the location of the proposed buildings, the stratigraphic units, and representative piles drilled into the deeper sand unit.
- generate an animation for a Superfund site in New Jersey to portray the vertical and horizontal extent of two adjacent but non-intersecting sources. The animation displayed the well locations with the sample concentrations represented by colored spheres and made readily identifiable the regions where the plumes may need to be remediated to meet regulatory standards.

Environ Corporation

www.environcorp.com

Environ used EVS-PRO to

- analyze the relative impact of two sources of contamination to an aquifer used as a municipal drinking water supply and allocate remedial costs accordingly. EVS-PRO was also used to display the results of MODFLOW and MT3D simulations that calculated the relative impact of

the sources at downgradient drinking water wells.

- investigate transport pathways to calculate and visualize the 3-D boundaries of soil contamination. Comparison of the vertical contaminant profile with the known geologic layers enabled the identification of preferential transport pathways (in this case, sand lenses). This information was key in selecting an appropriate and cost-effective remedy.

Conestoga-Rovers & Associates (CRA)

www.rovers.com

CRA has used EVS and MVS in the visualization of more than 30 sites in the United States in the last two years. A few typical tasks were as follows:

- to demonstrate the nature and extent of contamination in a multi-aquifer system underneath an active manufacturing facility and on-site landfill. Visualization presentations were given to company officials, community groups, and the Ohio Environmental Protection Agency. The use of EVS and MVS allowed for a clearer focus on the sources and extent of contamination. It also resulted in a greater understanding of the complex chemical and hydrogeological issues at the site, for all parties involved.
- to develop a model of aquifer and aquitard materials using indicator kriging. The resulting model challenged previous assumptions of a two-aquifer system divided by a clay aquitard and suggested potential pathways between the aquifers. The new model showed that much of the persistent contamination at the site was the result of dense NAPLs in the subsurface on the upgradient side of the site. The model was also used to aid in selection of both the location and type of remedial design.
- to visualize in three dimensions the results of MODFLOW and MT3D simulations of the spill of VOCs in an aquifer system. The site had a complex pumping history, with flow changing directions with time and also as a function of depth. The use of EVS allowed for a simple demonstration of how contaminants had migrated vertically and horizontally over the decades.
- to visualize the site, extent of contamination, and effect of remedial action for settlement negotiations for cost-recovery litigation in respect to a landfill, a former Superfund site, in New Jersey. Although the remedial action was

completed several years ago, cost-recovery had been ongoing.

The IT Group

www.theitgroup.com

IT used EVS-PRO to

- visualize TCE data to guide investigation and to aid in the determination of possible multiple sources at an active naval air station;
- visualize native geology in relation to fill and cut areas at a former treatment, storage, and disposal facility being closed under the Resource Conservation and Recovery Act (RCRA). EVS-PRO produced visualizations of removal of soil with heavy metal concentrations exceeding regulatory thresholds.

Hong Kong Geological Survey (HKGS)

HKGS used MVS for visualization and interpretation of complex geological conditions beneath reclaimed land at Tung Chung New Town, Lantau, Hong Kong. MVS was used to investigate, model, and visualize geological conditions, including the occurrence of marble xenoliths within a granite intrusion, development of karst with sinkholes, and extensive decomposition (weathering) of country rock. Site investigation data included about 1000 drill holes together with seismic reflection and microgravity surveys.

Frontline Environmental Management, Inc.

www.onthefrontlines.com

Frontline used EVS-PRO to

- delineate the extent of metal and polyaromatic hydrocarbon contamination of soil at a former starch plant. Statistical analysis provided the confidence needed to secure funding investment for redevelopment.
- visualize the results of groundwater flow modeling at a vinyl manufacturing facility located adjacent to one of Canada's "Heritage Rivers" and across from a municipal wellfield. The animations were used as a public communications tool.
- evaluate the contamination levels in soil adjacent to a former vinyl manufacturing facility, where site redevelopment involves realignment of a creek that is under the jurisdiction of the Canadian Department of Fisheries and Oceans.

- visualize the distribution of gasoline components (benzene, toluene, ethyl-benzene, and xylene) in soil and groundwater in three dimensions. EVS animation was used to demonstrate the changes in the volume of impacted subsurface materials that would occur with changes in required cleanup guideline concentrations.

Geosmica y Ambiente, Ltd., Bogota, Columbia

Geosmica is using MVS in a coal mine to calculate the volume of coal and the correlation of the coal-bearing and interstitial geologic layers and to design the coal pit for economical exploitation.

Section 6 — References

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Appendix A — Summary of Test Problems

Site A: Sample Optimization Problem

Site A has been in operation since the late 1940s as an industrial machine plant that used solvents and degreasing agents. It overlies an important aquifer that supplies more than 2.7 million gal of water per day for industrial, commercial, and residential use. Site characterization and monitoring activities were initiated in the early 1980s, and it was determined that agricultural and industrial activities were sources of contamination. The industrial plant was shut down in 1985. The primary concern is volatile organic compounds (VOCs) in the aquifer and their potential migration to public water supplies. Source control is considered an important remediation objective to prevent further spreading of contamination.

The objective of this Site A problem was to challenge the software's capabilities as a sample optimization tool. The Site A test problem presents a 3-D (3-D) groundwater contamination scenario where two VOCs, dichloroethene (DCE) and trichloroethene (TCE), are present. The data that were supplied to the analysts included information on hydraulic head, subsurface geologic structure, and chemical concentrations from seven wells that covered an approximately 1000-ft square. Chemical analysis data were collected at 5-ft intervals from each well.

The design objective of this test problem was for the analyst to predict the optimum sample locations to define the depth and location of the plume at contamination levels exceeding the threshold concentration (either 10 or 100 $\mu\text{g/L}$). Because of the limited data set provided to the analysts and the variability found in natural systems, the analysts were asked to estimate the plume size and shape as well as the confidence in their prediction. A high level of confidence indicates that there is a high probability that the contaminant exceeds the threshold at that location. For example, at the 10- $\mu\text{g/L}$ threshold, the 90% confidence level plume is defined as the region in which there is greater than a 90% chance that the contaminant concentration exceeds 10 $\mu\text{g/L}$. The analysts were asked to define the plume for three confidence levels—10% (maximum plume, low certainty, and larger region), 50% (nominal plume), and 90% (minimum plume, high certainty, and smaller region). The initial data set provided to the analyst was a subset of the available baseline data and intended to be insufficient for fully defining the extent of contamination in any dimension. The analyst used the initial data set to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence and better define the plume boundaries, the analyst needed to determine where the next sample should be collected. The analyst conveyed this information to the demonstration technical team, which then provided the analyst with the contamination data from the specified location or locations. This iterative process continued until the analyst reached the test problem design objective.

Site A: Cost-Benefit Problem

The objectives of the Site A cost-benefit problem were (1) to determine the accuracy with which the software predicts plume boundaries to define the extent of a 3-D groundwater contamination problem on a large scale (the problem domain is approximately 1 square mile) and (2) to evaluate human health risk estimates resulting from exposure to contaminated groundwater. The VOC contaminants of concern for the cost-benefit problem were perchloroethene (PCE) and trichloroethane (TCA).

In this test problem analysts were to define the location and depth of the PCE plume at concentrations of 100 and 500 $\mu\text{g/L}$ and TCA concentrations of 5 and 50 $\mu\text{g/L}$ at confidence levels of 10 (maximum plume), 50 (nominal plume), and 90% (minimum plume). This information could be used in a cost-benefit analysis of remediation goals versus cost of remediation. The analysts were provided with geological information, borehole logs, hydraulic data, and an extensive chemical analysis data set consisting of more than 80 wells. Chemical analysis data were collected at 5-ft intervals from each well. Data from a few wells were withheld from the analysts to provide a reference to check interpolation routines. Once the analysts defined the PCE

and TCA plumes, they were asked to calculate the human health risks associated with drinking 2 L/d of contaminated groundwater at two defined exposure points over the next 5 years. One exposure point was in the central region of the plume and one was at the outer edge. This information could be used in a cost-benefit analysis of reduction of human health risk as a function of remediation.

Site B: Sample Optimization and Cost-Benefit Problem

Site B is located in a sparsely populated area of the southern United States on a 1350-acre site about 3 miles south of a large river. The site is typical of many metal fabrication or industrial facilities because it has numerous potential sources of contamination (e.g., material storage areas, process activity areas, service facilities, and waste management areas). As with many large manufacturing facilities, accidental releases from laboratory activities and cleaning operations introduced solvents and other organic chemicals into the environment, contaminating soil, groundwater, and surface waters.

The objective of the Site B test problem was to challenge the software's capabilities as a sample optimization and cost-benefit tool. The test problem presents a two-dimensional (2-D) groundwater contamination scenario with three contaminants—vinyl chloride (VC), TCE, and technetium-99 (Tc-99). Chemical analysis data were collected at a series of groundwater monitoring wells on quarterly basis for more than 10 years along the direction of flow near the centerline of the plume. The analysts were supplied with data from one sampling period.

There were two design objectives for this test problem. First, the analyst was to predict the optimum sample location to define the depth and location of the plume at specified contaminant threshold concentrations with confidence levels of 50, 75, and 90%. The initial data set provided to the analyst was a subset of the available baseline data and was intended to be insufficient for fully defining the extent of contamination in two dimensions. The analyst used the initial data set to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence in defining the plume boundaries, the analyst needed to determine the location for collecting the next sample. The analyst conveyed this information to the demonstration technical team, who then provided the analyst with the contamination data from the specified location or locations. This iterative process continued until the analyst reached the design objective.

Once the location and depth of the plume was defined, the second design objective was addressed. The second design objective was to estimate the volume of contamination at the specified threshold concentrations at confidence levels of 50, 75, and 90%. This information could be used in a cost-benefit analysis of remediation goals versus cost of remediation. Also, if possible, the analyst was asked to calculate health risks associated with drinking 2 L/d of contaminated groundwater from two exposure points in the plume. One exposure point was near the centerline of the plume, while the other was on the edge of the plume. This information could be used in a cost-benefit analysis of reduction of human health risk as a function of remediation.

Site D: Sample Optimization and Cost-Benefit Problem

Site D is located in the western United States and consists of about 3000 acres of land bounded by municipal areas on the west and southwest and unincorporated areas on northwest and east. The site has been an active industrial facility since it began operation in 1936. Operations have included maintenance and repair of aircraft and, recently, the maintenance and repair of communications equipment and electronics. The aquifer beneath the site is several hundred ft thick and consists of three or four different layers of sand or silty sand. The primary concern is VOC contamination of soil and groundwater as well as contamination of soil with metals.

The objective of the Site D problem was to test the software's capability as a tool for sample optimization and cost-benefit problems. This test problem was a 3-D groundwater sample optimization problem for four VOC contaminants—PCE, DCE, TCE, and trichloroethane (TCA). The test problem required the developer to predict the optimum sample locations to define the region of the contamination that exceeded threshold concentrations for each contaminant. Contaminant data were supplied for a series of wells screened at

different depths for four quarters in a 1-year time frame. This initial data set was insufficient to fully define the extent of contamination. The analyst used the initial data set to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence in the prediction of the plume boundaries, the analyst needed to determine the location for collecting the next sample. The analyst conveyed this information to the demonstration technical team, who then provided the analyst with the contamination data from the specified location or locations. This iterative process was continued until the analyst determined that the data could support definition of the location and depth of the plume exceeding the threshold concentrations with confidence levels of 10, 50, and 90% for each contaminant.

After the analyst was satisfied that the sample optimization problem was complete and the plume was defined, he or she was given the option to continue and perform a cost-benefit analysis. At Site D, the cost-benefit problem required estimation of the volume of contamination at specified threshold concentrations with confidence levels of 10, 50, and 90%. This information could then be used in a cost-benefit analysis of remediation goals versus cost of remediation.

Site N: Sample Optimization Problem

Site N is located in a sparsely populated area of the southern United States and is typical of many metal fabrication or industrial facilities in that it has numerous potential sources of contamination (e.g., material storage areas, process activity areas, service facilities, and waste management areas). Industrial operations include feed and withdrawal of material from the primary process; recovery of heavy metals from various waste materials and treatment of industrial wastes. The primary concern is contamination of the surface soils by heavy metals.

The objective of the Site N sample optimization problem was to challenge the software's capability as a sample optimization tool to define the areal extent of contamination. The Site N data set contains the most extensive and reliable data for evaluating the accuracy of the analysis for a soil contamination problem. To focus only on the accuracy of the soil sample optimization analysis, the problem was simplified by removing information regarding groundwater contamination at this site, and it was limited to three contaminants. The Site N test problem involves surface soil contamination (a 2-D problem) for three contaminants—arsenic (As), cadmium (Cd), and chromium (Cr). Initial sampling indicated a small contaminated region on the site; however, the initial sampling was limited to only a small area (less than 5% of the site area).

The design objective of this test problem was for the analyst to develop a sampling plan that defines the extent of contamination on the 150-acre site based on exceedence of the specified threshold concentrations with confidence levels of 10, 50% and 90%. Budgetary constraints limited the total expenditure for sampling to \$96,000. Sample costs were \$1200 per sample, which included collecting and analyzing the surface soil sample for all three contaminants. Therefore, the number of additional samples had to be less than 80. The analyst used the initial data to define the areas of contamination and predict the location of additional samples. The analyst was then provided with additional data at these locations and could perform the sample optimization process again until the areal extent of contamination was defined or the maximum number of samples (80) was attained. If the analyst determined that 80 samples was insufficient to adequately characterize the entire 150-acre site, the analyst was asked to use the software to select the regions with the highest probability of containing contaminated soil.

Site N: Cost-Benefit Problem

The objective of the Site N cost-benefit problem was to challenge the software's ability to perform cost-benefit analysis as defined in terms of area of contaminated soil above threshold concentrations and/or estimates of human health risk from exposure to contaminated soil. This test problem considers surface soil contamination (2-D) for three contaminants—As, Cd, and Cr. The analysts were given an extensive data set for a small region of the site and asked to conduct a cost-benefit analysis to evaluate the cost for remediation to achieve specified threshold concentrations. If possible, an estimate of the confidence in the projected remediation areas was provided at the 50 and 90% confidence limits. For human health risk analysis, two

scenarios were considered. The first was the case of an on-site worker who was assumed to have consumed 500 mg/d of soil for one year during excavation activities. The worker would have worked in all areas of the site during the excavation process. The second scenario considered a resident who was assumed to live on a 200- by 100-ft area at a specified location on the site and to have consumed 100 mg/d of soil for 30 years. This information could be used in a cost-benefit (i.e., reduction of human health risk) analysis as a function of remediation.

Site S: Sample Optimization Problem

Site S has been in operation since 1966. It was an industrial fertilizer plant producing pesticides and fertilizer and used industrial solvents such as carbon tetrachloride (CTC) to clean equipment. Recently, it was determined that routine process operations were causing a release of CTC onto the ground; the CTC was then leaching into the subsurface. Measurements of the CTC concentration in groundwater have been as high as 80 ppm a few hundred ft down-gradient from the source area. The site boundary is approximately 5000 ft from the facility where the release occurred. Sentinel wells at the boundary are not contaminated with CTC.

The objective of the Site S sample optimization problem was to challenge the software's capability as a sample optimization tool. The test problem involved a 3-D groundwater contamination scenario for a single contaminant, CTC. To focus only on the accuracy of the analysis, the problem was simplified. Information regarding surface structures (e.g., buildings and roads) was not supplied to the analysts. In addition, the data set was modified such that the contaminant concentrations were known exactly at each point (i.e., release and transport parameters were specified, and concentrations could be determined from an analytical solution). This analytical solution permitted a reliable benchmark for evaluating the accuracy of the software's predictions.

The design objective of this test problem was for the analyst to define the location and depth of the plume at CTC concentrations exceeding 5 and 500 $\mu\text{g/L}$ with confidence levels of 10, 50, and 90%. The initial data set provided to the analysts was insufficient to define the plume accurately. The analyst used the initial data to make a preliminary estimate of the dimensions of the plume and the level of confidence in the prediction. In order to improve the confidence in the predicted plume boundaries, the analyst needed to determine where the next sample should be collected. The analyst conveyed this information to the demonstration technical team, who then provided the analyst with the contamination data from the specified location or locations. This iterative process continued until the analyst reached the design objective.

Site S: Cost-Benefit Problem

The objective of the Site S cost-benefit problem was to challenge the software's capability as a cost-benefit tool. The test problem involved a 3-D groundwater cost-benefit problem for a single contaminant, chlordane. Analysts were given an extensive data set consisting of data from 34 wells over an area that was 2000 ft long and 1000 ft wide. Vertical chlordane contamination concentrations were provided at 5-ft intervals from the water table to beneath the deepest observed contamination.

This test problem had three design objectives. The first was to define the region, mass, and volume of the plume at chlordane concentrations of 5 and 500 $\mu\text{g/L}$. The second objective was to extend the analysis to define the plume volumes as a function of three confidence levels—10, 50, and 90%. This information could be used in a cost-benefit analysis of remediation goals versus cost of remediation. The third objective was to evaluate the human health risk at three drinking-water wells near the site, assuming that a resident drinks 2 L/d of water from a well screened over a 10-ft interval across the maximum chlordane concentration in the plume. The analysts were asked to estimate the health risks at two locations at times of 1, 5, and 10 years in the future. For the health risk analysis, the analysts were told to assume source control preventing further release of chlordane to the aquifer. This information could be used in a cost-benefit analysis of reduction of human health risk as a function of remediation.

Site T: Sample Optimization Problem

Site T was developed in the 1950s as an area to store agricultural equipment as well as fertilizers, pesticides, herbicides, and insecticides. The site consists of 18 acres in an undeveloped area of the western United States, with the nearest residence being approximately 0.5 miles north of the site. Mixing operations (fertilizers and pesticides or herbicides and insecticides) were discontinued or replaced in the 1980s when concentrations of pesticides and herbicides in soil and wastewater were determined to be of concern.

The objective of the Site T sample optimization problem was to challenge the software's capability as a sample optimization tool. The test problem presents a surface and subsurface soil contamination scenario for four VOCs: ethylene dibromide (EDB), dichloropropane (DCP), dibromochloropropane (DBCP), and CTC. This sample optimization problem had two stages. In the first stage, the analysts were asked to prepare a sampling strategy to define the areal extent of surface soil contamination that exceeded the threshold concentrations listed in Table A-1 with confidence levels of 10, 50, and 90% on a 50- by 50-ft grid. This was done in an iterative fashion in which the analysts would request data at additional locations and repeat the analysis until they could determine, with the aid of their software, that the plume was adequately defined.

The stage two design objective addressed subsurface contamination. After defining the region of surface contamination, the analysts were asked to define subsurface contamination in the regions found to have surface contamination above the 90% confidence limit. In stage two, the analysts were asked to suggest subsurface sampling locations on a 10-ft vertical scale to fully characterize the soil contamination at depths from 0 to 30 ft below ground surface (the approximate location of the aquifer).

Table A-1. Site T soil contamination threshold concentrations

Contaminant	Threshold concentration (µg/kg)
Ethylene dibromide (EDB)	21
Dichloropropane (DCP)	500
Dibromochloropropane (DBCP)	50
Carbon tetrachloride (CTC)	5

Site T: Cost-Benefit Problem

The objective of the Site T cost-benefit problem was to challenge the software's capability as a cost-benefit tool. The test problem involved a 3-D groundwater contamination scenario with four VOCs (EDB, DCB, DBCP, and CTC). The analysts were given an extensive data set and asked to estimate the volume, mass, and location of the plumes at specified threshold concentrations for each VOC. If possible, the analysts were asked to estimate the 50 and 90% confidence plumes at the specified concentrations. This information could be used in a cost-benefit analysis of various remediation goals versus the cost of remediation. For health risk cost-benefit analysis, the analysts were asked to evaluate the risks to a residential receptor (with location and well screen depth specified) and an on-site receptor over the next 10 years. For the residential receptor, consumption of 2 L/d of groundwater was the exposure pathway. For the on-site receptor, groundwater consumption of 1 L/d was the exposure pathway. For both human health risk estimates, the analysts were told to assume removal of any and all future sources that may impact the groundwater. This information could be used in a cost-benefit analysis of various remediation goals versus the cost of remediation.

Appendix B — Description of Interpolation Methods

A major component of the analysis of environmental data sets involves predicting physical or chemical properties (contaminant concentrations, hydraulic head, thickness of a geologic layer, etc.) at locations between measured data. This process, called interpolation, is often critical in developing an understanding of the nature and extent of the environmental problem. The premise of interpolation is that the estimated value of a parameter is a weighted average of measured values around it. Different interpolation routines use different criteria to select the weights. Because of the importance of obtaining estimates of parameters between measured data points in many fields of science, a wide number of interpolation routines exist.

Three classes of interpolation routines commonly used in environmental analysis are nearest neighbor, inverse distance, and kriging. These three classes cover the range found in the software used in the demonstration and use increasingly complex models to select their weighting functions.

Nearest neighbor is the simplest interpolation routine. In this approach, the estimated value of a parameter is set to the value of the spatially nearest neighbor. This routine is most useful when the analyst has a lot of data and is estimating parameters at only a few locations. Another simple interpolation scheme is averaging of nearby data points. This scheme is an extension of the nearest neighbor approach and interpolates parameter values as an average of the measured values within the neighborhood (specified distance). The weights for averaging interpolation are all equal to $1/n$, where n is the number of data points used in the average. The nearest neighbor and averaging interpolation routines do not use any information about the location of the data values.

Inverse distance weighting (IDW) interpolation is another simple interpolation routine that is widely used. It does account for the spatial distance between data values and the interpolation location. Estimates of the parameter are obtained from a weighted average of neighboring measured values. The weights of IDW interpolation are proportional to the inverse of these distances raised to a power. The assigned weights are fractions that are normalized such that the sum of all the weights is equal to 1.0. In environmental problems, contaminant concentrations typically vary by several orders of magnitude. For example, the concentration may be a few thousand micrograms per liter near the source and tens of micrograms per liter away from the source. With IDW, the extremely high concentrations tend to have influence over large distances, causing smearing of the estimated area of contamination. For example, for a location that is 100 m from a measured value of 5 $\mu\text{g/L}$ and 1000 m from a measured value of 5000 $\mu\text{g/L}$, using a distance weighting factor of 1 in IDW yields a weight of 5000/1000 for the high-concentration data point and 5/100 for the low-concentration data point. Thus, the predicted value is much more heavily influenced by the large measured value that is physically farther from the location at which an estimate is desired. To minimize this problem, the inverted distance weight can be increased to further reduce the effect of data points located farther away. IDW does not directly account for spatial correlation that often exists in the data. The choice of the power used to obtain the interpolation weights is dependent on the skills of the analyst and is often obtained through trial and error.

The third class of interpolation schemes is kriging. Kriging attempts to develop an estimate of the spatial correlation in the data to assist in interpolation. Spatial correlation represents the correlation between two measurements as a function of the distance and direction between their locations. Ordinary kriging interpolation methods assume that the spatial correlation function is based on the assumption that the measured data points are normally distributed. This kriging method is often used in environmental contamination problems and was used by some DSS products in the demonstration and in the baseline analysis. If the data are neither lognormal nor normally distributed, interpolations can be handled with indicator kriging. Some of the DSS products in this demonstration used this approach. Indicator kriging differs from ordinary kriging in that it makes no assumption on the distribution of data and is essentially a nonparametric counterpart to ordinary kriging.

Both kriging approaches involve two steps. In the first step, the measured data are examined to determine the spatial correlation structure that exists in the data. The parameters that describe the correlation structure are calculated as a variogram. The variogram merely describes the spatial relationship between data points. Fitting a model to the variogram is the most important and technically challenging step. In the second step, the kriging process interpolates data values at unsampled locations by a moving-average technique that uses the results from the variogram to calculate the weighting factors. In kriging, the spatial correlation structure is quantitatively evaluated and used to calculate the interpolation weights.

Although geostatistical-based interpolation approaches are more mathematically rigorous than the simple interpolation approaches using nearest neighbor or IDW, they are not necessarily better representations of the data. Statistical and geostatistical approaches attempt to minimize a mathematical constraint, similar to a least squares minimization used in curve-fitting of data. While the solution provided is the “best” answer within the mathematical constraints applied to the problem, it is not necessarily the best fit of the data. There are two reasons for this.

First, in most environmental problems, the data are insufficient to determine the optimum model to use to assess the data. Typically, there are several different models that can provide a defensible assessment of the spatial correlation in the data. Each of these models has its own strengths and limitations, and the model choice is subjective. In principle, selection of a geostatistical model is equivalent to picking the functional form of the equation when curve-fitting. For example, given three pairs of data points, (1,1), (2,4), and (3,9), the analyst may choose to determine the best-fit line. Doing so gives the expression $y = 4x - 3.33$, where y is the dependent variable and x is the independent variable. This has a goodness of fit correlation of 0.97, which most would consider to be a good fit of the data. This equation is the “best” linear fit of the data constrained to minimization of the sum of the squares of the residuals (difference between measured value and predicted value at the locations of measured values). Other functional forms (e.g., exponential, trigonometric, and polynomial) could be used to assess the data. Each of these would give a different “best” estimate for interpolation of the data. In this example, the data match exactly with $y = x^2$, and this is the best match of this data. However, that this is the best match cannot be known with any high degree of confidence.

This conundrum leads to the second reason for the difficulty, if not impossibility, of finding the most appropriate model to use for interpolation—which is that unless the analyst is extremely fortunate, the measured data will not conform to the mathematical model used to represent the data. This difficulty is often attributed to the variability found in natural systems, but is in fact a measure of the difference between the model and the real-world data. To continue with the previous example, assume that another data point is collected at $x = 2.5$ and the value is $y = 6.67$. This latest value falls on the previous linear best-fit line, and the correlation coefficient increases to 0.98. Further, it does not fall on the curve $y = x^2$. The best-fit 2nd-order polynomial now changes from $y = x^2$ to become $y = 0.85x^2 + 0.67x - 0.55$. The one data point dramatically changed the “best”-fit parameters for the polynomial and therefore the estimated value at locations that do not have measured values.

Lack of any clear basis for choosing one mathematical model over another and the fact that the data are not distributed in a manner consistent with the simple mathematical functions in the model also apply to the statistical and geostatistical approaches, albeit in a more complicated manner. In natural systems, the complexity increases over the above example because of the multidimensional spatial characteristics of environmental problems. This example highlighted the difficulty in concluding that one data representation is better than another. At best, the interpolation can be reviewed to determine if it is consistent with the data. The example also highlights the need for multiple lines of reasoning when assessing environmental data sets. Examining the data through use of different contouring algorithms and model parameters often helps lead to a more consistent understanding of the data and helps eliminate poor choices for interpolation parameters.